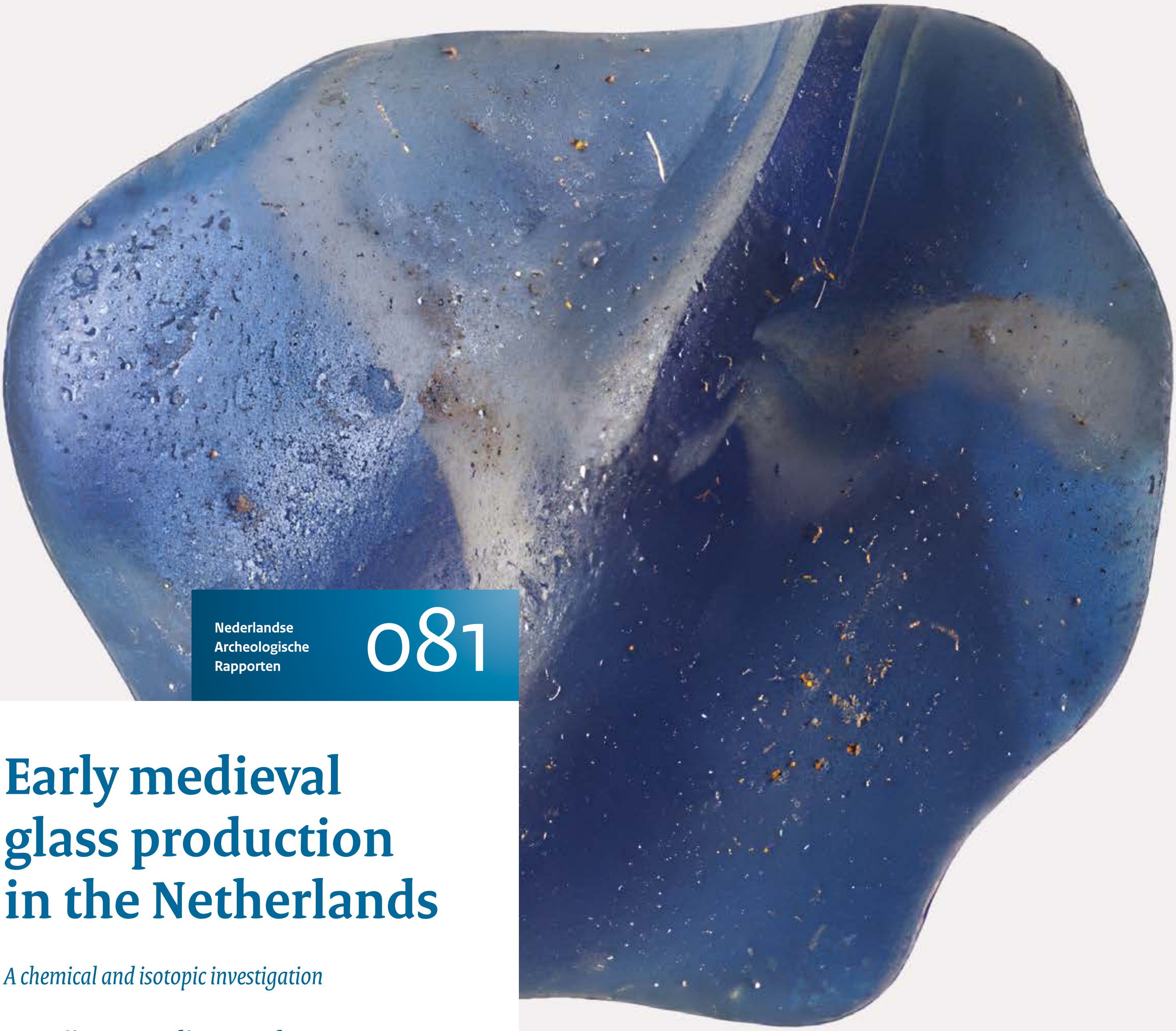
Cultural Heritage Agency
Ministry of Education, Culture and Science



Nederlandse Archeologische Rapporten 081

Early medieval glass production in the Netherlands

A chemical and isotopic investigation

Hongjiao Ma, Julian Henderson, Yvette Sablerolles, Simon Chenery and Jane Evans

Early medieval glass production in the Netherlands

a chemical and isotopic investigation

Hongjiao Ma, Julian Henderson,
Yvette Sablerolles, Simon Chenery
and Jane Evans

Colophon
Nederlandse Archeologische Rapporten 81
Early medieval glass production in the Netherlands: a chemical and isotopic investigation

Authors: Hongjiao Ma, Julian Henderson, Yvette Sablerolles (University of Nottingham), Simon Chenery and Jane Evans (British Geological Survey)
With a contribution from Menno Dijkstra (University of Amsterdam)

Authorisation: Hans Huisman and Rik Feiken (Cultural Heritage Agency of the Netherlands)

Illustrations (unless otherwise stated): Julian Henderson, Yvette Sablerolles and Marjolein Haars (BCL-Archaeological Support)

Cover design: J. Ranzijn (Happyfolio)

Cover: A selection of tesserae from the Wierum terp (province of Groningen) (Photograph: Jelle Schokker of the Noordelijk Archeologisch Depot).

Design and layout: Xerox/Osage

ISBN/EAN: 978-90-76046-85-3

Cultural Heritage Agency of the Netherlands
P.O. Box 1600
3800 BP Amersfoort
the Netherlands
www.cultureelerfgoed.nl

Contents

Summary

This monograph brings together for the first time comprehensive combined archaeological, technological and scientific investigations, using chemical (major, minor and trace element concentrations) and isotopic ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) analysis, of early medieval glass production in the Netherlands. We selected 276 samples of glass from Gennep, Maastricht (the Jodenstraat and Mabro sites), Wijnaldum-Tjitsma, Utecht (the Domplein and Oudwijker-dwarsstraat sites), Susteren-Salvatorplein, Wijk bij Duurstede (the Hoogstraat and vicus sites) and Deventer-Stadhuiskwartier, dating to between the late 4th and 11th centuries covering the Merovingian and Carolingian periods for compositional analysis. In addition, 20 samples were subjected to isotope analysis. The results of our trace element and isotopic analyses have provided new and highly significant insights into early medieval glass production in the Netherlands.

Several different compositional types of glass have been identified. Both high and low lead glasses have been found along with pristine and recycled (sub-types of) natron glass (HIMT, Foy 2, Egypt II, Levantine II), plant ash glass, wood ash glass and mixed-alkali glass. The best evidence in early medieval Europe for the on-site production of the lead-tin yellow and tin oxide colorant/opacifier in crucibles excavated from the 6th-7th century AD Jodenstraat site in Maastricht is discussed in detail. It is associated with comprehensive evidence for the manufacture of brightly coloured monochrome glass beads (also found at Wijnaldum), a craft specialisation. The base glass for the beads was imported 'pristine' Foy 2 glass. Our results show that a higher proportion of Merovingian glasses were imported 'pristine' (Egyptian) glasses than the glasses used in the Carolingian period, when the majority of glasses were recycled, potentially multiple times. While it is often suggested that elevated levels of antimony and lead started to occur in the Carolingian period we have found elevated levels already in Merovingian glasses, an indication that a small proportion of Roman tesserae and/or coloured Roman vessel glass was being added to the glass melt then.
By combining trace element and isotope analysis we have been able to demonstrate that Carolingian recycled glass contained a small proportion of wood ash glass. Wood ash glass with elevated concentrations of Cs, Rb, Ba and Sr started to be manufactured in Europe from around 800 AD and added to natron glass to produce mixed alkali glass. Even though mostly recycled glass was in use by this time much of the Dutch natron glass can still be attributed an ultimate source in Egypt (recycled Foy 2 glass), with limited evidence for the use of 'pristine' glass. Our analyses provides evidence that recycled Foy 2 was still in use as late as the mid 10th century AD.

When the results of our analyses for Carolingian natron glasses are compared with contemporary (7th-11th century AD) northern Italian glasses from the site of Comacchio and Spanish glasses from Tolmo de Minateda an interesting contrast is revealed. Both sets of glasses are largely recycled: whereas Dutch recycled natron glass has an ultimate source in Egypt, the recycled natron glasses from Comacchio and Tolmo de Minateda show far more evidence for the use of imported Levantine glasses instead. Only a single example of Levantine (II) glass has been found amongst Dutch early medieval glass with no evidence that such glass formed part of the recycling process. This is a clear reflection of differing trade contacts and glass supplies between northern and southern Europe. By the 9th-11th centuries AD the widest range of glass types was in circulation and, perhaps surprisingly, glass from Deventer includes pristine glass. The glass from Deventer consists of thirteen natron glasses (three Roman, three pristine Egyptian II, six recycled Foy 2, one pristine Foy 2), one plant ash glass, four mixed alkali glasses and nineteen wood ash glasses. Like plant ash glass production in western Asia, the primary production of wood ash glass would have formed a decentralised network because wood ash was also widely available.

Although glass beads were certainly made in the Netherlands along the Meuse valley in the Merovingian period, probably with a 'permanent' workshop in Maastricht (even if the bead makers took part in other industries) we suggest that bead workers were mobile further north, visiting Rijnsburg, Wijnaldum and perhaps Valkenburg-De Woerd. A very likely source of vessel glass probably existed in Cologne. Scientific analysis of Merovingian bowls and beakers (450-550 AD) shows a correlation between vessel type, chemical composition and colour, suggesting that glass of specific colours were selected during vessel manufacture. This may simply

have been part of batch production but we suggest that colour selection was related to a memory of the exotic origin of the glass and drinking rituals, including the colour of liquid the vessels contained.

We have shown that the key types of raw glass were from Egypt- Foy 2 and HIMT in the Merovingian period and Egypt II in the Carolingian period; a single Levantine II (punty) glass is the only example of Levantine glass we have found; mixed-alkali glass probably derived from northern France; wood ash glass perhaps from Belgium, northern France or more likely from Germany (perhaps using the Viking trade network); plant ash glass was imported from western Asia as beads and raw glass (also perhaps by the Vikings); the raw glass was made into characteristic early medieval vessel types and incorporated into glass beads.

Samenvatting

Deze monografie combineert voor het eerst uitgebreid archeologisch, technisch en natuurwetenschappelijk onderzoek, met chemische (hoofd- en sporenelementen) en isotopenanalyses ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$), van vroegmiddeleeuwse glasproductie in Nederland. We selecteerden 290 glasmonsters uit Gennep, Maastricht (Jodenstraat en Mabro), Wijnaldum-Tjitsma, Utrecht (Domplein en Oudwijkerdwarsstraat), Susteren-Salvatorplein, Wijk bij Duurstede (Hoogstraat en vicus) en Deventer-Stadhuiskwartier, die met dateringen tussen de late vierde en de elfde eeuw de Merovingische en Karolingische perioden beslaan. Daarnaast werden twintig van deze monsters geselecteerd voor isotopenanalyse. De resultaten van de sporenelement- en isotopenanalyses geven belangrijke nieuwe inzichten in de vroegmiddeleeuwse glasproductie in Nederland.
Er zijn verschillende typen glas met verschillende samenstelling geïdentificeerd. Zowel glas met hoge als met lage gehaltes aan lood zijn aangetroffen, naast vers en gerecycled natron glas (sub-typen HIMT, Foy 2, Egypte II, Levantine II), glas op basis van de as van planten of hout en gemengd alkali glas. Het meest overtuigende bewijs voor de lokale productie van lood-tin geel en tin oxide als kleurstof en opacifier in vroegmiddeleeuws Europa - smeltkroesjes uit de zesde-zevende eeuw n.Chr. opgegraven in Maastricht Jodenstraat - wordt in detail besproken. Tijdens de opgraving is er uitputtend bewijs gevonden voor het maken van helder gekleurde monochrome kralen, een gespecialiseerd ambacht. Het basisglas voor de kralen was geïmporteerd "vers" glas van type Foy 2.
Onze resultaten laten zien dat een hoger percentage van Merovingisch glas bestond uit geïmporteerd "vers" (Egyptisch) glas, vergeleken met glas uit de Karolingisch periode, toen het meeste glas werd gerecycled – één of meerdere keren. Hoewel vaak wordt gesuggereerd dat verhoogde gehaltes aan antimoon en lood pas beginnen in de Karolingische tijd, doordat kleine hoeveelheden Romeinse tesserae of glas van Romeins glazen vaatwerk werden toegevoegd aan gesmolten glas, vonden we al verhoogde gehaltes van antimoon en lood in Merovingisch glas. Met een combinatie van sporenelement- en isotopenanalyses hebben we kunnen aantonen dat Karolingische gerecycled glas een klein aandeel hout-as glas bevat. Hout-as glas met verhoogde concentraties van cesium (Cs), rubidium (Rb), barium (Ba) en strontium (Sr) werd voor het eerst geproduceerd in Europe vanaf ongeveer 800 n.Chr., en het werd toegevoegd aan natronglas om gemengd alkaliglas te maken. Hoewel in deze periode vooral gerecycled glas in gebruik was, kan veel van het Nederlandse natronglas nog steeds worden gelinkt aan een oorspronkelijk herkomst in Egypte (gerecycled Foy 2 glas), met beperkte aanwijzingen voor het gebruik van "vers" glas. Onze analyses laten zien dat gerecycled Foy 2 glas zelfs nog in gebruik was in het midden van de tiende eeuw n.Chr.
Als de resultaten van onze analyses van Karolingisch natron glas worden vergeleken met contemporain (zevende-elfde eeuws) Noord-Italiaans glas uit Comacchio en Spaans glas uit Tolmo de Minateda komt een interessant contrast aan het licht. De assemblages bestaan vooral uit gerecycled glas, maar terwijl het Nederlandse gerecycled glas in oorsprong uit Egypte komt, bevat het glas uit Comacchio en Tolmo de Minateda aanwijzingen voor een Levantijnse oorsprong. Slechts één voorbeeld van Levantijns (II) glas is aangetroffen onder Nederlands vroegmiddeleeuws glas, en er zijn geen aanwijzingen dat dit soort glas een rol speelde bij recycling. Dit is een duidelijke weerslag van verschillen in handelscontacten en glasleveringen tussen Noord- en Zuid-Europa.
In de negende-elfde eeuw was de variatie in glastypes die werden gebruikt het grootst, inclusief – wellicht verrassend – "vers" glas uit Deventer. Het glas uit Deventer bestaat uit dertien stuks natron glas (drie keer Romeins, drie keer "vers" Egyptisch II, zes keer gerecycled Foy 2, een keer "vers" Foy 2), een keer plant-as, vier keer gemengd alkali en negentien keer hout-as glas. Net als plant-as glasproductie in West-Azië vormde de productie van hout-as glas een decentraal netwerk omdat hout as algemeen beschikbaar was.
Hoewel Merovingische glazen kralen zeker werden gemaakt in Nederland in de Maasvallei, waarschijnlijk met een permanente werkplaats in Maastricht (zelfs als de kralenmakers ook andere ambachten uitoefenden), waren de kralenmakers verder naar het noorden waarschijnlijk mobiel. Daar bezochten ze Rijnsburg, Wijnaldum en mogelijk ook Valkenburg – de Woerd. Keulen was hoogstwaarschijnlijk een belangrijke bron voor glazen kommen en bekers. Natuurwetenschappelijke analyse van

Merovingische kommen en bekers (450-550 n. Chr.) tonen een correlatie tussen typologie, chemische samenstelling en kleur, wat suggereert dat glas met specifieke kleuren werd geselecteerd voor deze toepassing. Dit zou simpelweg onderdeel kunnen zijn van grootschalige productie, maar we suggereren dat de selectie van de glaskleur te maken had met herinneringen aan de exotische herkomst van het glas en drankrituelen, inclusief de kleur van de vloeistof die in de glazen had gezeten.
We hebben laten zien dat de belangrijkste types ruw glas tijdens de Merovingische periode Egypte – Foy en HIMT - waren, en tijdens de Karolingische periode Egypte II. Het enige voorbeeld van Levantijns glas is een Levantijns II puntige glastype. Gemengd alkaliglas kwam waarschijnlijk uit Noord-Frankrijk, hout-as glas mogelijk uit België, Noord-Frankrijk of Duitsland (wellicht via het Viking handelsnetwerk verkregen). Plant-as glas kwam uit West-Azië als kralen en ruw glas (ook wellicht via de Vikingen); het ruwe glas werd verwerkt tot typische vroeg-middeleeuwse kommen en bekers, en tot glazen kralen.

1 Introduction

1.1 The research project 'Early medieval glass production'

The research project 'Early medieval glass production' was one in a series of studies referred to as Pre-Malta research ('*pre-Malta onderzoek*'), and as such falls under the programme Knowledge for Archaeology. The programme aims to obtain datasets from (not yet fully elaborated) excavation data before the introduction of the Valetta convention in 2007. With the use of currently developed research methods and techniques, the Pre-Malta research programme enables the study of archaeological remains from old excavations, which means that substantial new knowledge can be obtained about the past.

This research project involved a series of important goals related to the production technology, provenance, glass supply, recycling, trade and use of early medieval glass in the Netherlands, building on, and expanding significantly on, existing published research.

The main goals were:

- To carry out a full chemical and isotopic analysis of all available glass samples using cutting edge techniques.
- To establish the raw materials used to make the transparent, translucent and opaque glasses samples.
- To consider whether the glass has been recycled.
- To attempt to suggest a source for the glass (i.e. provenance).
- To investigate the change in glass raw materials over time.
- To establish if there are any sub- and supra-regional supply patterns for unrecycled early medieval glass found on Dutch early medieval sites from within Europe, the Levant, Iraq and Iran.
- To investigate in more detail whether there are chronological changes in the use of pure imported as opposed to recycled glass moving from the Merovingian into the Carolingian period.
- To compare the glass compositions and technologies used in the manufacture of glass beads and vessels and investigate if there is evidence for the use of raw material specialization.
- To establish if there is any evidence for local specialisation of glass bead production as reflected in their chemical compositions.
- To investigate the evidence for the production of lead-tin oxide opacified glass found in the Netherlands given the large number of crucibles containing a yellow substance that have been discovered in early medieval Dutch contexts especially in Maastricht and whether there is evidence for primary glass making.

Scope of the research project

The project focuses on the simple, monochrome beads, raw materials and production waste from Merovingian and Carolingian contexts along with contemporary vessel glasses.[1] A small number of glasses dating to *c.* 900-1000 AD are included for comparison. The examination of polychrome beads and glass vessels have been included because they provide information to (better) answer the research questions. The starting point for this project's research is Henderson and Sablerolles' research plan from 2020. This plan is included as an appendix in the report *'An Overview of Dutch Early Medieval glassworking, published chemical and isotopic analyses of glass beads and vessels, raw material provenance of beads and vessels, changes in raw material use over time and a plan for future scientific analysis'*, which served as preparation for this project.[2] The substantive information from that report has been largely incorporated into this report.

1.2 Research questions

The central questions of the study are:

1. What raw materials were used in the local production of simple, monochrome Early Medieval beads?
2. Where were these raw materials obtained from?

Sub-questions here are:

i. What substances were used to make the different colours of glass in the artefacts tested?
ii. What compositional groups can be distinguished in the glasses based on chemical analyses?

[1] Between AD 480 and 987.
[2] Henderson & Sablerolles 2020.

iii. What does this tell us about dating of primary glass production of these groups?
iv. What do the isotope ratios (Sr, Nd) obtained from the glasses of selected compositional types tell us about the their origin and dating?
v. What networks inside and outside the Netherlands were used in obtaining glass, including the colourants used?
vi. To what extent were the raw materials or semi-finished products derived from primary production, or to what extent from systematic recycling of glass, including Roman?

The research also provides building blocks for two NOaA questions[3]:

- What are the nature, manifestations, extent and context of craft specialization? (NOaA 2.0 question 67)
- Where do non-local raw materials of utilitarian objects come from? (NOaA 2.0 question 139)

1.3 Research approach

We have been able to carry out a comprehensive scientific analysis of a wide range of early medieval glass samples and production waste. The scientific techniques we used were Scanning Electron Microscopy, Electron Probe Microanalysis, Laser Ablation Inductively Coupled Plasma Mass Spectrometry and Thermal Ion Mass Spectrometry, resulting in the largest database of chemical and isotopic analyses for early medieval Dutch glass.

The Covid-19 virus prevented us from travelling and taking new samples which made it difficult to plan and led to delays in scientifically analysing some samples. We had hoped to work on new glass samples excavated from secure archaeological contexts. Although possible for glass from Maastricht, Utrecht, Gennep, Wijnaldum, Susteren and Deventer, the context information for Dorestad glasses studied here were unavailable at the time of sampling in the early 1990s. It was nevertheless possible to provide dates for the Dorestad glass according to vessel form.

This project has involved a collaborative team of archaeologists, archaeological scientists and a geologist: Hongjiao Ma, Julian Henderson, Yvette Sablerolles, Simon Chenery, Jane Evans and Menno Dijkstra linking archaeologists, archaeological scientists and geologists.

[3] https://noaa.cultureelerfgoed.nl.

1.4 Structure of the monograph

The remaining chapters of the monograph develop in a logical sequence. Chapter 2 provides essential information about early medieval European glass technologies, including raw materials, evidence of European early medieval glass production outside the Netherlands, the types of glass found in early medieval Europe followed by a review of published results for early medieval glass from the Netherlands. Chapter 3 discusses the existing archaeological evidence for early medieval glass production on the Netherlands.

In Chapter 4 the sites from which glass samples used in this study are introduced briefly followed by a description of the three main analytical techniques used to investigate the samples chemically and isotopically: electron probe microanalysis (EPMA), laser ablation-inductively coupled plasma- mass spectrometry (LA-ICP-MS) and thermal ion mass spectrometry (TIMS). Chapter 5 presents and discusses the results of the chemical and isotopic analyses of the glass and crucible samples.

Chapter 6 is a synthesis of archaeological and scientific results according to chronological periods (450-550, 550-650, 650-750, 750-850 and 850-1000 AD) for the work together with conclusions. Chapter 7 provides succinct answers to the research questions and sub-questions listed in Section 1.2 above.

1.5 Acknowledgements

We are grateful to W. Dijkman, Senior Conservator Archeologie en Erfgoed, Team Programma en Innovative, Centre Céramique–Kumulus – Natuurhistorisch Museum, Maastricht for allowing us to sample glass and glass working material from Maastricht, to H. Wynia, the municipal archaeologist of Utrecht for allowing us to sample glass from Utrecht, to J. Schokker of the Noordelijk Archeologisch Depot for allowing us to sample glass from Wijnaldum, A. Peddemors then curator at the Rijksmuseum van Oudheden, Leiden for permission to sample glass from Dorestad, W. van Es of the Rijksdienst voor het

Oudheidkundig Bodemonderzoek also for permission to sample Dorestad glass and to E. Mittendorff, project leader archaeology, Deventer for sending us glass from Deventer so that we could sample it and both the former director of the Provincial Limburgs Museum in Venlo, G. Jansen and H. Stoepker, for permission to sample glass from Susteren. We are also grateful to Dr. A. Kronz of Göttingen University for sharing some unpublished data. We are very grateful for the support of H. Huisman and R. Feiken of the Cultural Heritage Agency of the Netherlands for being extremely supportive and for being very flexible throughout the project, at the very difficult time of Covid. Finally we are grateful to Dr Matthew Delvaux for permission to reproduce Figure 3.7 and Bill Bolton for producing publishable versions of all the Figures.

2 Technology and raw materials used for Dutch early medieval glass

2.1 Introduction

This chapter provides the basic background information about Dutch early medieval glass technology including a discussion of the raw materials used which can be suggested from glass chemical compositions and the furnaces used for making the likely sources of glass in Europe and western Asia. The main primary raw materials are an alkaline flux, a silica source and a calcium source. Fluxes are provided by natron, plant ash or wood ash; silica is normally provided by sand; calcium is provided by shell fragments in sand or calcium compounds in plant ash or wood ash . Mineral rich colorants were added separately to these glasses or opacifiers were developed from them by heat treating the glasses.
The chapter covers glass production dating to between the late Hellenistic period and the early Islamic period as well as evidence for centralized and decentralized production organisations.
It also discusses the compositional evidence for the recycling of glass in the second half of the 1st millennium AD.

A separate sub-section (Section 2.3) is devoted to a discussion of the evidence for the early medieval glass industry outside the Netherlands, especially in Belgium, Denmark France, Germany, Hungary, Ireland, Italy and the United Kingdom. The next sub-section (Section 2.4.1) discusses the main compositional types of glass in some cases associated with primary glass making sites such as in Syro-Palestine, Egypt, Syria, Iraq and northern Europe. The main compositional types are pristine Egyptian and Levantine natron glasses, Roman glass, HIMT and its variations, plant ash glass, mixed-alkali glass and wood ash glass. Section 2.4.2 is a summary of the existing published chemical analyses of early medieval Dutch glass from Maastricht, Susteren, Dorestad, Rijnsburg, Wijnaldum, Lent, Borgharen and Sittard with interim interpretations.

2.2 Furnaces, raw materials and glass sources

Most early medieval glass found in the Netherlands is what is known as soda-lime (natron) glass. From about the 2nd century BC, during the Late Hellenistic period, this kind of glass was fused from raw materials in massive rectangular tank furnaces. The earliest example of a tank furnace yet discovered is in Beirut, possibly dating to the 2nd century BC.[4] Roman glass tank furnaces have also been found, in Egypt[5] and Syro-Palestine, such as Jalame.[6] The Levant continued to be the primary centre for the production of raw furnace natron glass on a massive scale into the Byzantine period, especially in the 6th–8th centuries AD[7] with a probable dip in the scale of production in the early Byzantine period.

The glass fused in these tank furnaces from raw materials attached itself to the floor of the furnace and, once it had cooled down, would have been removed, perhaps with a pickaxe, to produce chunks of raw furnace glass.[8] These chunks would then have been reheated in a crucible within a second furnace type, perhaps of a beehive shape.[9] This would then have enabled the glass-workers to work the glass into a range of glass artefacts using metal implements such as gathering rods to make beads, and hollow tubes, known as blowing irons, for blowing glass into vessels. This second stage of glass production is known as secondary production. It could have occurred on the same site as where the glass was fused (primary glass production) or on other sites at a distance from where the glass was fused.[10] Raw furnace glass manufactured at primary glass making centres was sometimes traded by boat. Excavations of shipwrecks have revealed the extent of the trade, such as the 3rd century BC Sanguinaire found off the coast of Corsica which had at least 550 kg of glass including raw glass[11], the 2nd-3rd century AD Mljet wreck off the Croatian coast produced about 100 kg of raw glass[12] and the 2nd-3rd century AD Ouest Embiez 1 (Var) which produced between 350 and 700 kg of raw glass chunks, each weighing up to 25 kg.[13] Furthermore raw glass has been excavated from the Golfe de Fos near the mouth of the Rhône[14] and two metric tons of raw glass came from the early 11th century wreck at Serçe Limani, Turkey.[15]

4 Kouwatli *et al.* 2008.
5 Nenna 2015, 19.
6 Phelps *et al.* 2016.
7 Gorin-Rosen 2000; Tal, Jackson-Tal & Freestone 2004; Nenna 2015; Freestone *et al.* 2000; Phelps *et al.* 2016.
8 Gorin-Rosen 2000.
9 Henderson 2000, 38–42.
10 Henderson 1989; Freestone *et al.* 2000; Phelps *et al.* 2016, Henderson *et al.* 2021.
11 Alfonsi & Gandolfi 1997.
12 Rossi 2009.
13 Fontaine & Foy 2007.
14 Foy & Nenna 2001.
15 Bass 1984; Bass *et al.* 2009.

The presence of geographically separated primary and secondary glass-making sites has led to a suggested decentralized model for classical glass production in western Asia.[16] The discovery of raw furnace glass on sites where there is no evidence for primary glass production either suggests that it was being traded through the site or that it was worked on the site. The existence of crucibles with a layer of glass on the inside supports the latter suggestion and there are examples of this from early medieval contexts in the Netherlands (see Chapter 3 for information about the industrial evidence for glass production in the Netherlands). There is no archaeological evidence for the primary manufacture of translucent or transparent natron glass in the early medieval Netherlands.

Natron glass was manufactured from a combination of sand and a mineral flux called natron or natrun.[17] The sand that occurs on the coastal beaches of the Levant is ideal for glass production and is referred to as such by both Strabo and Pliny.[18] The second primary raw material was natron. The main source of this evaporite mineral flux was in the Egyptian western desert at Wadi el Natrun,[19] close to some primary production sites for Roman glass.[20] This mineral is an evaporite which is formed seasonally and would have been shipped or traded to glass makers on the Levantine coast. A third crucial component of natron glass, which gives it durability, is lime.

Lime was provided by the marine shells in the sand. It appears that the proportion in the Levantine coastal sand was just right for the production of durable natron glass. It is possible that the shell fraction was separated by glass makers and mixed with sand in the correct proportion prior to glass production, though no archaeological evidence for this has been found. The availability of sand with these characteristics would have been one reason why primary glass-making furnaces were located on the Levantine coast. Both archaeological and scientific evidence confirms that this is the case. Strontium and neodymium isotope and mineralogical analysis of multiple beach deposits around the Mediterranean has suggested which sands would have been suitable for glass making.[21]

In spite of the existence of important Byzantine glass-making sites in the Levant in the 6th–8th centuries a range of political, social and economic factors would not necessarily provide a guarantee that fresh natron glass would have found its way to early medieval glass-working sites in the Netherlands.

While it is widely accepted that some form of natron glass (whether pristine or recycled) was used for the manufacture of early medieval objects in the Netherlands (to be discussed in much more detail below and in Chapter 5) there is one source of fully fused coloured glass that was also used: glass tesserae.[22] Evidence for the reuse of these cubes of generally opaque glass has been discussed in many archaeological and scientific studies and this study is no exception. Their discussion is relevant in this section because they were coloured and opacified: such colourants and opacifiers were also sometimes used in Dutch early medieval glass.

Roman glass tesserae are invariably made from natron glass. Most are opacified with small crystals, especially of calcium antimonate ($Ca_2Sb_2O_7$ or $Ca_2Sb_2O_6$). Without additional colourants this produces an opaque white colour.[23] Opaque yellow tesserae are coloured by lead antimonate crystals ($Pb_2Sb_2O_7$) with a smaller number of opaque yellow tesserae coloured with lead stannate crystals ($Pb_2Sn_2O_7$). Dull red tesserae are opacified and coloured with copper droplets also found in Roman enamels.[24] Opaque turquoise blue tesserae are coloured with copper and calcium antimonate, opaque yellow-green tesserae with copper and lead antimonate; opaque blue tesserae are coloured by a combination of cobalt and calcium antimonate. Therefore if elevated levels of antimony, lead, copper and sometimes tin are found in translucent early medieval glass a likely source is recycled Roman glass tesserae.[25] Alternatively, such elevated levels of colourants can be explained by the use of fragments of highly coloured vessel glass. The most significant collection of glass tesserae in the Netherlands has been discovered at Wierum.[26]

Dutch early medieval glass was also coloured deliberately with low levels of transition metal ions: cobalt to produce a deep translucent blue colour, copper for a turquoise colour and manganese for a purple colour. Various shades of green, amber and pale blue could be produced by modifying the furnace atmosphere in which the glass was melted if the glass contained iron and manganese. Amber and

16 Henderson 1989; Freestone *et al.* 2000.
17 Shortland 2004; Henderson 2013, 51–53.
18 Henderson 2013, 51–52.
19 Henderson 2013, 52.
20 Nenna 2015.
21 Brems et al 2013a; 2013b.
22 Boschetti *et al.* 2016; Henderson, Sode & Sablerolles 2019; Crocco *et al.* 2021.
23 Lahlil *et al.* 2010; Boschetti *et al.* 2016; Boschetti *et al.* 2020.
24 Henderson 1991a; Barber, Freestone & Moulding 2009.
25 Schibille & Freestone 2013; Boschetti *et al.* 2016; Henderson, Sode & Sablerolles 2019.
26 Henderson, Sode & Sablerolles 2019; Crocco *et al.* 2021.

pale blue colours are produced in an oxygen-deficient furnace atmosphere, green in a more oxidising atmosphere.

There is evidence for the production of one particular colour of glass in northwestern Europe before *c.* 800 AD and as early as the 6th century: opaque yellow. Opaque yellow vitreous materials have been found in crucibles from several early medieval sites in Ireland, Denmark and the Netherlands. The evidence for its production and its scientific analysis will be discussed in more detail in Chapter 5.

From around 800 AD, glass technology in western Asia underwent a technological transition, especially during the Abbasid caliphate. The Abbasid glassmakers had a marked effect on glass technology in the western Asia and the Mediterranean: instead of natron they made glass using ashes of salt-tolerant shrubby plants. These plants grew in semi-desert, evaporitic and maritime environments in western Asia and parts of the Mediterranean basin. Because the plants used for the flux could grow in inland locations, one result was that primary glass production became more widespread across western Asia and into central Asia. This led to a fully decentralized production system with multiple primary production centres, many located in cosmopolitan hubs on the silk road.[27] In inland locations suitable plants were far more accessible as a source of flux than the far more limited sources of the evaporitic mineral used by the Romans to make natron glass.

Like the Romans, the Abbasids fused glass raw materials (plant ashes and sand) in large tank furnaces[28] and added colourants to the glass to produce deeply coloured glasses as part of the secondary phase of production. It is worth noting that, unlike natron, these plants had a highly variable composition depending on a range of environmental factors. One of these is the geological nature of the soil in which the plants grew. Although this might be viewed as potentially confusing, using scientific analysis has enabled plant ash glasses to be provenanced in increasingly more geographically defined ways (see below). Although the Muslims were partly responsible for this transition in glass production the other possible influence on this technological change was the pre-Islamic manufacture of plant ash glass by the Sasanians between the 3rd and 7th centuries[29] in modern Iran and Iraq for which there is no published direct evidence for primary glass production from raw materials. It is nevertheless likely that the glass was made at sites like Veh Ardašīr and Ctesiphon[30] and Brill[31] has suggested -based on the presence of tank furnace fragments found on rural sites, some of probable Sasanian date - that this is evidence for primary glass production. Most of the glass found in early medieval northwestern Europe, including Dutch contexts, dating to after *c.* 800 AD therefore shows a dependence on the import of ready-made glass combined with a transition that occurred in western Asian glass technology, with the production and export of plant ash glass, especially in the Carolingian period.

The exception to this dependence on imported glass made in the Mediterranean basin and western Asia (with associated recycling during in the Carolingian period) was the use of some of the earliest glass fused from raw materials in northwestern Europe, from tree ashes. Some of the earliest examples date to the 8th century, for example from the Loire valley in France.[32] However, its production became widespread in the 11th century and later, especially in response to the massive demand for cathedral and church windows, such as in the Weald of Kent in southern England, and France,[33] but the period between *c.* 800 and 1000 AD was one of transition too.[34]

One of the hallmarks of the technological transition in early medieval northwestern Europe is the occurrence of mixed-alkali glass, a likely combination of different proportions of wood ash glass and natron glass. It is more likely that fully fused glasses were mixed than that wood ash was added to natron glass. This would have formed part of a period of experimentation with the new alkali raw material – wood ash. Like the plant ash used to make glass in western Asia discussed above, wood ash has a highly variable chemical composition depending on the geological characteristics of the soil in which the tree grew, the tree species, the season in which the ash is burnt and the part of the tree.[35] As with plant ash glass it is becoming increasing clear that in some cases scientific analysis can help to provide a geographical provenance (often regional) for such glasses.[36] From around 800 AD glass linen smoothers make an appearance in early medieval Europe. Scientific analysis has revealed that these were made in Europe using glassy slags derived from lead-silver cupellation.[37]

27 Henderson *et al.* 2021; Henderson 2022.
28 Aldsworth *et al.* 2002; Henderson *et al.* 2005a; Henderson *et al.* 2021.
29 Mirti *et al.* 2008; Mirti *et al.* 2009.
30 Simpson 2014, 204.
31 Brill 2005, 66.
32 Aunay *et al.* 2020.
33 Wedepohl 2008; Meek, Henderson & Evans 2012; Henderson 2013, 104–108.
34 Henderson 2013, 97–108; Aunay *et al.* 2020.
35 Jackson, Booth & Smedley 2005.
36 Meek, Henderson & Evans 2012; Adlington *et al.* 2019.
37 Gratuze *et al.* 2003.

Summarizing, the main types of glass in use in Early Medieval North-Western Europe, and therefore potentially available in the Netherlands, were:

- imported pristine raw furnace natron glass;
- recycled and mixed natron glass (including tesserae);
- imported pristine plant ash glass (made from shrubs);
- wood ash glass made in northwestern Europe;
- mixed-alkali glass (mixed wood ash and natron glass)

2.3 Evidence for the glass industry in early medieval Europe outside the Netherlands

Evidence for the glass industry in early medieval Europe is quite sparse. Glass furnaces have been found at Glastonbury (UK), associated with the evidence for glass working,[38] and Paderborn (Germany).[39] The evidence from Paderborn and Glastonbury is only for glass working, not glass making (the fusion of raw materials) and Paderborn is probably later. The evidence at Glastonbury consists of a furnace, a crucible fragment with green glass adhering, lumps of glass, spills of glass, a moil (the glass encircling the tip of a blowpipe constituting production waste which does not get recycled), pulls of glass, a cast slab and a bichrome cable as well as vessel and window glass fragments.
A possible glass furnace associated with glass fragments and bichrome cables has also been found at Barking in London.[40] Glass furnaces have also been found at Huy (Belgium).[41]

Evidence for glass working in the form of crucibles containing glass, dribbles and drops of glass, melted glass rods and cables, half made beads, vessels and window glass has been found (either separately or together) at a variety of places. Evidence for beadmaking has been found at Ribe (Denmark)[42] and at Dunmisk (Ireland),[43] where glass studs were also made. Some other places have yielded evidence for glass blowing, including the abbeys of Stavelot (Belgium)[44] and San Vincenzo al Volturno (Italy).[45] Other evidence has been found at the Carolingian monasteries of Lorsch and Corvey (Germany)[46] and Zalavar (Hungary).[47]

There is also clear evidence that glass was worked at Cologne during both the Merovingian and Carolingian empires.[48] Evidence of glass production consists of fragments of glass furnace floors, which were presumably beehive-shaped furnaces,though no plans of the excavations are published so it is difficult to judge. Multiple crucible fragments with glass adhering, dribbles and drops of glass, reticella rods, scraps of glass, tesserae and vitrified bricks have been found. A distribution of Merovingian loop decorated bowls down the Rhine has been recorded suggesting that they were made in Cologne mainly from HIMT-2 glass (see below).[49] Koch has shown that there is also a distribution of early Merovingian cone beakers down the Rhine, further supporting Rhenish production, probably in Cologne.[50]

At Hedeby (Germany) a possible glass-working area was found, including a possible furnace.[51] Two crucible fragments containing wood ash glass, a single one with high lead glass combined with wood ash and soda-lime glass and raw glass have been reported.[52] Evidence for glass production has also been found at Cordel (Germany) although an early medieval date has been called into question.[53]

Scientific analysis of the glass from Cologne using electron probe microanalysis alone shows that secondary glass making involved HIMT-2, which was originally probably fused in the early to mid 4th century AD, and was mainly used to make funnel and bell beakers – as well as funnel beakers from Hedeby (Germany).[54] A plot of weight % Fe_2O_3/TiO_2 versus Fe_2O_3/Al_2O_3 provides evidence of a single funnel beaker from Cologne made with Egypt-2 glass (originally made between *c.* 720 and 780 AD), and funnel beakers from Hedeby made from Egypt-1 glass (originally made between *c.* 760/780 and 870 AD).

However, unless failed examples of funnel beakers and moils, both of the appropriate chemical composition, are discovered it is difficult to be absolutely certain that the vessels were blown in Cologne from weak HIMT (HIMT-2), although it remains likely. Being the commonest glass compositional type at the time, weak HIMT is clearly not diagnostic to a specific production centre. Therefore, Cologne has provided evidence for glass working but not definite proof for the manufacture of funnel beakers there.

38 Willmott & Welham 2013; 2015.
39 Wedepohl, Winkelmann & Hartmann 1997; Gai 2005.
40 Willmott & Welham 2015.
41 de Sigoyer *et al.* 2005.
42 Andersen & Sode 2010.
43 Henderson & Ivens 1992.
44 Van Wersch *et al.* 2014.
45 Dell'Acqua 1997.
46 Sanke, Wedepohl & Kronz 2002.
47 Szöke, Wedepohl & Kronz 2004.
48 Dodt, Kronz & Simon 2021.
49 Dodt, Kronz & Simon 2021, Abb. 10.
50 Koch 1987.
51 Stepphun 1998, 94–96, Abb. 24.
52 Kronz *et al.* 2016.
53 Haevernick 1979.
54 Dodt, Kronz & Simon 2021, Abb. 11.

2.4 Scientific analysis of early medieval glass in Europe

2.4.1 The principal glass types

Syro-Palestinian and Egyptian glass
The primary characterization of pristine Levantine and Egyptian natron glass was carried out by Nenna *et al.*,[55] Foy *et al.*,[56] Freestone *et al.*,[57] Phelps *et al.*,[58] Freestone *et al.*[59] and Schibille *et al.*[60] These studies focused on glass which derived from primary glass-making sites in the Syro-Palestinian area and Egypt and shows that different proportions of minerals such as zircons, chromite and feldspars can characterize the sands used to make glasses at different production sites and at different times. Two compositional groups of natron glass produced in Israel in the mid-late first millennium AD have been widely recognized so far. Levantine I is defined according to the chemical compositions of sixth to seventh century glass from Dor and Apollonia. The sand used for making Levantine I glass was probably derived from the Bay of Haifa, close to the mouth of the river Belus of antiquity. As Phelps *et al.*[61] have noted the use of the term Levantine I has masked other compositionally related but distinct glass, such as that made at 4th century Jalame. Levantine II was defined using the chemical composition of furnace glass produced at Bet Eli'ezer and is dated to the 8th century Late Byzantine – Umayyad period.[62]

Two compositional groups were recognized by Gratuze and Barrandon[63] in their study of early Islamic glass coin weights from Egypt. Since then the two groups have been referred to as Egyptian I and Egyptian II.[64] Egyptian I glass typically has high alumina (3–4.5 wt%) and low lime (3–4 wt%).[65] It has been suggested that this glass was produced in factories near the famous natron source at Wadi el Natrun. Egyptian II glass has relatively high lime (c. 9%) and low alumina (typically 1.5–2.5%). Recent detailed analysis of Egyptian natron glasses has revealed the existence of Egypt 1A dating to before 725 AD, Egypt 1B dating to between 720 and 780 AD and Egypt 2 dating to between 760/780 and 870 AD.[66]

Because these glasses from different primary production sites have clear compositional characteristics, they should be identifiable amongst early medieval Dutch glass. It has been noted that the levels of sodium oxide decreased[67] and aluminium oxide increased over time[68] in these pristine glasses, due to a shortage of natron, and the use of different sand deposits, respectively.

Other natron glass
Tesserae
When glass tesserae made out of natron glass were mixed with other natron glass to extend its volume, certain compositional characteristics in the tesserae are passed on to the bulk glass. As discussed above the occurrence of elevated levels of antimony, copper, lead and sometimes tin in translucent vessel glass suggests that a stock of glass tesserae has been mixed into the bulk glass.[69] Elevated levels of antimony indicate this especially because calcium antimonate was used almost universally as the opacifier in a high proportion of Roman glass tesserae.

HIMT and its variations
High iron, manganese and titanium (HIMT) oxide levels that are found in 4th–5th century HIMT natron glass indicate a probable Egyptian source.[70] High levels of these oxides as well as zirconium show that sands with high proportions of minerals bearing these elements were used to make the glass. A higher iron variation has also been identified.[71]

Much work has been carried out to investigate variations of HIMT glasses which have been found in the Mediterranean and in northern Europe. The most important variation of HIMT *sensu stricto* is the Foy 2 compositional group. Foy 2 was originally identified in glass from Carthage[72] and includes 6th century series 2.1, which contains elevated V, Ti and Zr, and series 3.2 as originally described by Foy and colleagues.[73] These types of glass are regarded as 'weaker' types of HIMT with lower concentrations of iron, manganese and titanium and variously labelled HLIMT (high lime, iron, manganese and titanium),[74] weak HIMT[75] and HIMT 2. Foy 2.2 was originally defined by Foy and colleagues as a recycled version of Foy 2.1.[76] This type of glass may have been recycled multiple times and is found across the Mediterranean and Europe in contexts dating to as late as the 9th century.[77] The ultimate origin of the original base glass used in these glasses – which would then have been recycled

55 Nenna, Vichy & Picon 1997.
56 Foy *et al.* 2003.
57 Freestone, Gorin-Rosen & Hughes 2000.
58 Phelps *et al.* 2016.
59 Freestone *et al.* 2018.
60 Schibille *et al.* 2019.
61 Phelps *et al.* 2016.
62 Freestone, Gorin-Rosen & Hughes 2000.
63 Gratuze & Barrandon 1990.
64 Freestone, Gorin-Rosen & Hughes 2000.
65 Wt% = percentage of each oxide by weight.
66 Schibille *et al.* 2019.
67 Henderson 2002.
68 Phelps *et al.* 2016.
69 Henderson 1991a; Schibille & Freestone 2013; Boschetti *et al.* 2016; Henderson, Sode & Sablerolles 2019; Crocco *et al.* 2021.
70 Foy *et al.* 2003.
71 Ceglia *et al.* 2015.
72 Schibille, Sterrett-Krause & Freestone 2016.
73 Foy *et al.* 2003.
74 Ceglia *et al.* 2019.
75 Conte *et al.* 2014.
76 Foy *et al.* 2003.
77 Bertini, Henderson & Chenery 2020.

and mixed with other glasses – was probably Egypt, with elevated proportions of heavy minerals such as zirconium characterizing Egyptian glass.

Foy 2.1 high iron found in Byzantine glass weights[78] has also been recognized in Anglo-Saxon Britain, Serbia, Merovingian France and Spain.[79] Furthermore, another compositional variation, HIT (high iron and titanium), has been recognized from 5th–6th century Bulgaria[80] and possibly from 5th–6th century Albania.[81] HIT is unlikely to have been made in Egypt or the Levant; where it was made precisely is unknown. A plant ash variant of the Foy 2 family has been recognized by Schibille *et al.*[82] in Byzantine glass weights.

Plant ash glass

From *c.* 9th century AD plant ash glasses manufactured in the Islamic domain in western Asia and the southern Mediterranean were made in cosmopolitan centres along the silk roads stretching from Spain to central Asia.[83] Because local sources of plant ashes were used to make the glass their chemical and isotopic characteristics relate to the geological or geographical location in which they were made. A range of minor and trace elements, including their ratios, can be used to characterize the raw materials used to make the glasses, such as Ca, Mg, Ba, Zr, Ti, Cs/K, Li/K, Li/Na, B/Na, 1000Zr/Ti, La/Ti, Cr/La, Ce/Zr, Y/Zr, Mg/Ca.[84]

Examples of plant ash glasses that have been found amongst early medieval European glass are millefiori, blob decorated, melon and chopped beads from 10th century Viking age burials at Peel on the Isle of Man,[85] a colourless silver foil glass bead from Wijnaldum,[86] the blue cable applied to the rim of an 8th–9th century pale green funnel beaker from Dorestad,[87] in the matrices of two 9th century trail-decorated funnels and in the body of a funnel beaker as well as beads found at Susteren.[88] For a closer consideration of Susteren examples see below, and the use of trace element analysis in Chapter 5. Dekówna[89] reports the analysis of eight artefacts, a glass drop, a rod, five segmented beads and an annular bead from Hedeby (Germany) that are plant ash glasses opacified with lead stannate. Kronz *et al.*[90] note that some plant ash glasses from Hedeby were mixed with lead. Moreover, typical Islamic millefiori glass beads have been found at Dorestad.[91]

Like the distribution of Islamic coins (dirhams),[92] it appears that Islamic plant ash glasses are mainly restricted to the northern Netherlands, Scandinavia and the Baltic, coinciding with the presence of Vikings, and far fewer examples have been found in France,[93] with negligible numbers in Germany until the 9th century.[94]

Mixed-alkali glass

Most glasses with mixed-alkali compositions that have been published mainly date to the 9th–10th centuries, reflecting the transition from natron to wood glass technology in northern Europe. There is no doubt that wood ash glass was made in northern Europe. Mixed-alkali glasses have been found at Hedeby (Germany)[95] including a single funnel beaker,[96] and at Paderborn (Germany)[97] with two examples from the abbey at Fulda (Germany) with relative potassium oxide/soda levels of 7.7/6.6 and 6.0/9.1.[98]

Two pre-851 and an 11th–12th century AD (possibly redeposited) mixed-alkali green window glass have been found at Lurk Lane, Beverley (UK).[99] Two examples of mixed-alkali glass have also been found at Dorestad: a late 8th century yellow-green palm funnel[100] and a 9th century AD yellow-green funnel beaker.[101] The analysis of a yellow-green tubular base of a classic funnel beaker from Susteren was also of a mixed-alkali composition.[102]

Comprehensive evidence for mixed-alkali glass working has been found at the *c.* 800–866 AD Carolingian site of Méru, Oise (France). The archaeological evidence is in the form of furnace walls and crucibles containing glass. Both natron glass and glasses with potassium oxide levels of between *c.* 2% and 12% were found. This potentially suggests that Méru was one possible location where the mixture of wood ash and natron glass or, less likely, the addition of wood ash to natron glass, actually occurred[103] although the case is not completely proven. It is also suggested that mixing of natron and wood ash glass occurred at Hedeby in Germany.[104]

Wood ash glass

High potassium levels were introduced using wood ash as a flux. High potassium glasses have been published from the abbey of Stavelot (Belgium).[105] These glasses are quite early, from

78 Schibille *et al.* 2016.
79 Ares *et al.* 2019.
80 Smith, Henderson & Faber 2016.
81 Conte *et al.* 2014.
82 Schibille *et al.* 2016.
83 Henderson *et al.* 2021.
84 Henderson *et al.* 2016; Siu *et al.* 2020; Schibille *et al.* 2020.
85 Henderson 2002, Table 1, analyses 13, 22–25, 31, 41, 48 and 49.
86 Henderson 1999, 288, Table 2, analysis 32.
87 Sablerolles & Henderson 2012, analysis 129.
88 Henderson 2023.
89 Dekówna 1980, Table 44.
90 Kronz *et al.* 2016.
91 Langbroek 2021b.
92 Jankowiak 2021.
93 Aunay *et al.* 2020; Pactat *et al.* 2017.
94 Kronz *et al.* 2016.
95 Dekówna 1978, Tables 2 and 4; Dekówna 1980, Table 48, nos. 3, 4.
96 Kronz *et al.* 2016.
97 Wedepohl, Winkelmann & Hartmann 1997.
98 Kind, Kronz & Wedepohl 2002, Table 2.
99 Henderson 1991b, 129, Catalogue numbers 240 and 250, Appendix; Henderson 1993.
100 Henderson 2012.
101 Henderson 2012.
102 Henderson 2023.
103 Pactat *et al.* 2017.
104 Kronz *et al.* 2016.
105 Van Wersch *et al.* 2014.

contexts dating to between the second half of the 7th century to the early 9th century AD. The twelve examples are characterized by soda levels of below 3%, potassium oxide levels of between 10.14% and 20.21% and calcium oxide levels of between 13.84% and 20.23%. All contain high magnesium oxide and phosphorus pentoxide levels; the rest of the glass from the site is natron glass – there is no plant ash glass. In addition, full wood ash window glasses characterized by very high potassium and calcium oxide levels like those from Stavelot have been found in probable late 8th to early 9th century AD contexts at Baume-les-Messieurs, Jura (France).[106] Wood ash glasses have also been found at the church of St Hermès-et-Alexandre (Belgium).[107]

In Germany wood ash glass has been found at ecclesiastical sites, at the abbeys of Lorsch, Corvey, Brunshausen–Gendersheim and Fulda.[108] Excavations of the 10th century site of La Milesse, Sarthe (France) has produced large-scale evidence for working high potash glasses. The glasses that were scientifically analysed had a relatively restricted compositional range which led Pactat *et al.*[109] to suggest that the glass was fused there. Kronz *et al.*[110] have reported the presence of nine funnel beakers made with wood ash (out of a total of 61 wood ash glasses) and two crucibles containing wood ash glass from Hedeby (Germany). It was noted that wood ash glass contains higher calcium oxide levels in glass that dates to post 1200; the range detected was between *c.* 10% and 22% with the majority being between *c.* 10% and 16%.[111] Some of the earliest wood ash glasses contain up to about 11% calcium oxide, such as from Hedeby. Six funnel beakers from Borg in Norway[112] dating to between 800 and 1000 AD contain between 11.2 and 12.7% calcium oxide.

High lead glass has been reported from a variety of northern European sites. The first high lead glass appears *c.* 10th century AD. Four examples have been reported from Hedeby with 22 other glasses being a mixture of plant ash glass and lead.[113]

Glass making in early medieval Europe therefore only involved wood ash to produce high potassium glasses. Before around 800 AD glass-workers relied on the import of scrap and raw glass which was either formed directly into objects or mixed with other glass.

2.4.2 Summary of existing scientific analyses of early medieval Dutch glass before the start of this project

Scientific analysis of early medieval glasses from Maastricht, Susteren, Wijk bij Duurstede (Dorestad), Rijnsburg, Wijnaldum, Lent, Borgharen and Sittard had already been carried out prior to this study. What follows is a brief summary of the results from these investigations.

Maastricht

The early medieval glass and glass-bearing objects from Maastricht[114] include a good number of glass beads (including failed beads), glass rods and crucibles with vitreous materials attached. Seventeen glass crucibles with colourless, pale green and opaque yellow residues attached were discovered at Jodenstraat and are discussed in much more detail in Chapter 5. Apparently sintered material was attached to one of the crucibles found at the Mabro site and it was suggested that this might possibly be frit (though see Chapter 5).

The results of the analyses are given as means and standard deviations for each glass colour, for window glass samples and for two separate samples of crucible glass.[115] Using these results, a translucent blue splinter of glass resulting from glass working could possibly be of a pristine Levantine glass (but see Chapter 5). The glass is coloured with 0.1% cobalt oxide in the presence of 0.2% cupric oxide. The three window fragments contain elevated MgO, K_2O, TiO_2 and MnO, with low antimony oxide concentrations, so are likely to be recycled/mixed glass varieties of weak HIMT. Yellow-green glass from inside a crucible is contaminated with 8.7% Al_2O_3; it contains low CaO (3%) as well as elevated TiO_2 and Fe_2O_3. It is therefore difficult to estimate what its original composition was, especially if the same elements (e.g. Al and Fe) were present both in the original glass and in the crucible wall from which they migrated into the glass. Colourless glass attached to another crucible wall has very similar elemental contamination.

The opaque yellow residues (n=4) contain the highest PbO levels (30.6±10.02) associated with tin oxide because they relate to the production of lead-tin oxide ($Pb_2Sn_2O_7$/Pb_2SnO_4).

106 Van Wersch *et al.* 2015.
107 Van Wersch, Mathis & Hoffsummer 2009.
108 Sanke, Wedepohl & Kronz 2002; Kind, Kronz & Wedepohl 2002; Wedepohl 2003.
109 Pactat *et al.* 2017.
110 Kronz *et al.* 2016.
111 Kronz *et al.* 2016, Abb. 9.
112 Henderson & Holand 1992.
113 Kronz *et al.* 2016.
114 Sablerolles, Henderson & Dijkman 1997.
115 Sablerolles, Henderson & Dijkman 1997, Table 2.

They contain slightly elevated MgO and relatively high manganese and iron oxides of above 1%. The opaque white residues (n=2) contain high tin oxide and lower lead oxide because they are opacified with tin oxide crystals. These opaque white residues also contain higher magnesia levels (1.3±0.2%) than the opaque yellow glasses, something that has been found in Roman opaque white enamels and tesserae.[116]

The four opaque red glasses analysed contain only slightly elevated levels of magnesia and potassium oxide (means of 1.15% and 0.83% respectively). High levels of ferrous oxide (3.8±0.63%) may indicate that iron-rich crystals contribute to the red colour (see Chapter 5 for a more detailed interpretation); 0.37% ZnO possibly indicates that brass filings were used as a source of copper colourant. Two opaque green glasses which contain elevated MgO (with a mean of 1.2%) are coloured with cupric oxide (mean of 4%). They are opacified with lead stannate. Zinc has also been detected, suggesting that brass was added as the copper source. A single opaque turquoise glass was probably opacified with lead-tin oxide. It is coloured with 2.3% CuO and contains elevated MgO at 1.2%.

Susteren

Six beads, eleven vessels, two crucibles and ten windows were analysed using electron probe microanalysis and Scanning Electron Microscopy.[117] The glass beads and vessels are primarily of natron glass having similar compositional characteristics to those from Wijnaldum and Maastricht. All contain between 0.74% and 0.83% MgO. In beads 4 and 6 the K_2O levels are above 1%. In most cases the TiO_2 levels are between 0.1% and 0.2%; bead 5 contains 0.22% TiO_2. These natron glasses contain between 2.49% and 2.76% Al_2O_3 with the exception of bead 6 which contains 3.05% Al_2O_3. Being beads the glasses are coloured in various ways: the 'black' (deep translucent brown) body of bead 1 is coloured with 5.09% Fe_2O_3; a combination of MnO and Fe_2O_3 has produced the green colour in the bodies of beads 2, 5 and 6. Most of the translucent bead bodies (and opaque decoration) contain low levels of Sb, Pb and Cu oxides – an indication of a level of recycling involving the addition of coloured Roman glass, including tesserae (which are invariably coloured and opacified with $Ca_2Sb_2O_7$). The bodies of beads 3 and 4 contained high levels of magnesia, potassium oxide and phosphorus pentoxide and are therefore plant ash glasses. Bead 4 contains the lowest concentration of Al_2O_3 at 2.06%.

The eleven glass vessels from Susteren that were analysed consist of nine soda-lime natron glasses, one mixed-alkali glass (no. 19) and one plant ash glass (no. 28). The natron glasses contain between 0.76% and 1.2% MgO, up to 1.24% K_2O and some have elevated P_2O_5 (e.g. no. 23 with 0.37%). TiO_2 concentrations range from 0.09% (no. 25) to 0.4 (no. 26) so are variations of HIMT.

The Susteren vessel glasses are colourless, cobalt blue, blue-green, pale green and pale yellow. The pale yellow glass is probably coloured with ferrous oxide. All glasses contain elevated concentrations of CuO, Sb_2O_3 and PbO. No copper was detected in the colourless sample (no. 26). These oxides are indications of mixing and recycling.

The mixed-alkali glass (no. 19), a pale green funnel beaker with a tubular base, contains 8.76% Na_2O and 8.5% K_2O. It also contains 3.69% MgO, 1.5% P_2O_5 and 9.73% CaO all of which are quite distinctive characteristics associated with the inclusion of an organic flux. The blue-green plant ash glass *trechterbeker* fragment (no. 28) contains the lowest Al_2O_3 (2.03%) of the vessel glasses showing that a purer silica source was used. It is also characterized by 4.2% MgO and 2.48% K_2O.

The opaque red, yellow and white decorative elements used on beads 2, 3, 4, 5 and 6 mainly follow the same pattern of colourant use as discussed for the Wijnaldum and Maastricht opaque glasses: elevated Fe (4.59%) and CuO_2 (1.74%) in red glass, high PbO and SnO_2 in opaque yellow (probably in the form of $Pb_2Sn_2O_7$ crystals) as well as a combination of Pb and Sb which are probably responsible for opaque yellow (in the form of $Pb_2Sb_2O_7$ crystals) in the decoration of bead 5.

Wijk bij Duurstede (Dorestad)

Forty two vessels, one glass chip, five tesserae, one rod and two linen smoothers were analysed using electron probe microanalysis.[118] Of these, 39 of the vessels are of a soda-lime natron glass composition. The remaining three consist of one plant ash blue trail from the rim of a *trechterbeker*

116 Henderson 1991a.
117 Henderson 2023.
118 Henderson 2012.

(no. 129b), and two potassium (wood ash) palm funnel (late 8th century) and funnel beaker (9th century) glasses (nos 103 and 136). These contain relatively low potassium oxide levels at 8.6% and 7.9% respectively, associated with 1.6% and 1.2% soda levels and 14.1% and 13.8% calcium oxide levels. These represent early examples of wood ash glasses.

All the natron glass has very similar characteristics to those already discussed for Wijnaldum, Maastricht and Susteren. The glasses contain between 2.1% and 3.34% Al_2O_3 but mainly fall between 2.5% and 3.0%, CaO concentrations of between 5.85% and 8.59% and P_2O_5 at 0.37% and 1.8%. Some contain slightly elevated levels of MgO and K_2O and some elevated levels of P_2O_5 and MnO. Unsurprisingly, such characteristics suggest that the glasses have been recycled or mixed and are weak HIMT.

The 32 Dorestad blue-green and pale green vessel glasses are coloured by a combination of MnO and Fe_2O_3, some with Fe_2O_3 levels up to 2.7%. The greenish translucent glasses are also coloured with CuO levels up to 2%. There is a statistically coherent number of pale green/nearly colourless as opposed to blue-green vessel fragments from Dorestad. There is some evidence that the pale green and especially the nearly colourless glasses contain lower Al_2O_3 than blue-green glasses, though there are exceptions. MnO levels in all shades of green are at similar levels, mainly at between 0.5% and 0.7%. The combination of MnO and Fe_2O_3 will impart colour to the pale green glass given a specific oxidizing/reducing atmosphere in the glass furnace. The elevated CuO levels in the blue-green glass therefore appear to provide the deeper green colour. The lower Al_2O_3 in the pale green and colourless glass suggests that the glass was made with a slightly different sand source from the blue-green glasses.

The blue plant ash glass trail used to decorate a *trechterbeker* (no. 129a) is coloured with cobalt oxide (0.06%). The body of the nearly colourless beaker decorated with gold foil might be expected to be a purer glass but it has a very similar 'intermediate'/Foy 2 composition to other green Dorestad glasses with no obvious use of a decolourizer or evidence that a 'special' glass was used. However, the furnace atmosphere must have been controlled carefully to produce the colourless glass. The red beaker base contains 2.73% Fe_2O_3 and 1.51% Cu_2O associated with 0.66% ZnO and 1.4% PbO. The copper-rich colourant (probably in the form of cuprite droplets) used may therefore well have included scrap brass.

Rijnsburg

Thirteen Merovingian glass samples from the glass-working site of Rijnsburg were analysed using electron probe microanalysis. Six were beads or unfinished beads, six were rods and one was a sample of crucible glass.[119] The only translucent glass is a turquoise rod of a natron composition.

All the yellow glasses were opacified with lead-tin oxide and both white glasses opacified with SnO_2 but unusually they contained low levels of MgO, whereas seven other opaque white early medieval glasses from Maastricht and Wijnaldum contain elevated MgO levels.[120] It can be suggested that the Rijnsburg white glasses were made at a separate source from other white glasses. Although only two red glasses were analysed the same thing is true for them: neither of them contain elevated MgO and K_2O, something that is found almost universally in other early medieval opaque red glasses.

The chemical compositions of the two red and two orange glasses from Rijnsburg are quite different from each other. The red glasses contain much higher Fe_2O_3 than detected in the orange glasses (5.7% and 3.2% versus 0.8% and 0.5% respectively). On the other hand, the orange glasses contain 20% and 18% Cu_2O as opposed to 5.7% and 3.2% Cu_2O in the red glasses. The orange glasses are therefore likely to contain denser and larger Cu_2O crystals than the opaque red glasses. The latter are liable to be in the form of micron sized copper droplets or cuprite. The opaque yellow material on the inside of the crucible fragment consists almost entirely of Pb(O) and $Sn(O_2)$: 79.8% and 11% respectively, with 4% SiO_2 and may be evidence for production of lead-tin pigment on site.

Wijnaldum

The scientific analysis of the glass and glass-bearing artefacts from Wijnaldum reported on 38 electron microprobe analyses of twelve vessels dating to between 450 and 900 AD, 24 beads dating between 550 and 900 AD, a vitreous blob attached to a crucible dated to 250–350 AD and glass attached to a crucible

119 Dijkstra, Sablerolles & Henderson 2011.
120 Dijkstra, Sablerolles & Henderson 2011, fig. 12.

dating to between 575 and 620 AD.[121] The translucent glasses are mainly glass vessels; three are glass beads. The beads are mainly deliberately coloured with the oxides of transition metals, manganese, iron and copper. Opacification is due to the formation of tin oxide, SnO_2 (white), lead-tin oxide $Pb_2Sn_2O_7$ (yellow) and cuprous oxide Cu_2O (red).[122] High iron associated in the opaque red glasses would have acted as an internal reducing agent.

Apart from one, the translucent glass samples are natron glass containing elevated MnO and Fe_2O_3. The exception is a single drawn segmented silver foil bead which has a full plant ash composition with much higher levels of MgO (5.5%) and K_2O (2.2%) which are comparable with Islamic glasses found at Hedeby.[123] Elevated MgO levels of *c.* 1% are present in two vessel glasses; the earliest glass vessel dating to *c.* 450 AD contains 0.3% TiO_2 which is also unusually high – its significance will be discussed below. Three colourless glasses were analysed, one of which is the silver foil bead. One glass is probably decolourized with 0.4% antimony trioxide. Some translucent glasses also have trace levels of TiO_2, CuO, Sb_2O_3, SnO_2 and PbO, all indicators of glass recycling or mixing, including the use of Roman glass tesserae.

The dull opaque red glass bead contains high potassium and magnesium oxides, a characteristic of Roman enamels and tesserae[124] so this is evidence that this kind of glass continued to be used in the early medieval period. An opaque red globular bead contains unusually high CaO (11.7%) and relatively low Al_2O_3 (1.9%). The presence of tin suggests that scrap bronze was used as a copper-rich colourant in the bead; tin is absent from the other opaque red beads. All red glass beads contain lead ranging from 1.2% to 14.2%. An orange bead is opacified with copper in the presence of iron, the orange rather than red colour was possibly attributable to differences in the sizes of copper crystals in the glasses. Lead stannate in crystalline form is the opacifier in opaque yellow-green glass beads (numbers 18 and 23) which are otherwise coloured with copper and iron respectively. The opaque yellow glasses contain between 21.5% and 54.5% PbO and are opacified with $Pb_2Sn_2O_7$/$Pb_2Sn_2O_6$ crystals. The opaque yellow material on the inside of the flat tray or less likely a furnace fragment (number 38) contains 63.5% PbO. It may have been a flat plate on which the opaque yellow residue was heated probably at *c.* 650°C. It is clear from the composition that the glass-like material is contaminated by interaction with the ceramic substrate. A single vitreous blob from a crucible that was analysed (number 37) contains high Al_2O_3 (9.7%), 63.5% PbO and 2% total alkali – it is probably a fuel ash slag.

Both an opaque yellow tessera and the yellow spiral trail decorating the rim of a beaker from Wijnaldum are opacified with lead antimonate.

Though opaque glasses contain elements associated with their colour and opacity they also can contain elevated MgO, K_2O, CoO, CuO. The presence of these oxides could suggest that the base soda glass used to make the opaque glasses was recycled, though more detailed analysis of opaque yellow glasses in Chapter 5 provides interesting new information.

Lent

Corbella[125] used p-XRF to analyse 30 glass beads that were found in four graves in the Merovingian cemetery of Lent. Most glasses are probably of a natron composition with additives to modify the glass colours. It was not possible to analyse sodium. In this case the data should be treated as indicative because it's possible that different colour compositions were combined in one analysis. The red glasses analysed contained elevated potassium, iron and copper as found in other such glasses. The detection of MgO was unreliable. Two of the glasses analysed apparently contained alumina levels above 4% with relatively low CaO so potentially might have originated in south Asia. The white glass analysed contained low tin and elevated antimony so may be opacified with calcium antimonate. Two green glasses may be coloured with a combination of iron and manganese oxides.

Borgharen

The results of semi-quantitative analyses of the glasses from Borgharen produced using p-XRF are listed according to their colour.[126] The opaque white glasses mainly contain tin with low levels of antimony and are therefore likely to be opacified with SnO_2 crystals. However, some very high levels of P_2O_5 have been listed. If these are so high, which does not seem likely, then bone ash needs to be considered as a possible white opacifier. Opaque blue glasses are also apparently opacified with tin oxide. The glasses

121 Henderson 1999.
122 Henderson 1985; Matin 2019.
123 Steppuhn 1998, 100–101.
124 Henderson 1991a; Silvestri *et al.* 2012.
125 Corbella 2017.
126 Van Os *et al.* 2014.

contain relatively low levels of lead oxide. According to these results, the same opacifier was used in opaque brown glasses. The colourless glass may have been clarified with manganese oxide. The translucent green glass seems to contain tin and lead so may be semi-opaque. The opaque orange glass contains *c.* 6% PbO and unusually high CaO. A compositionally quite consistent series of eight opaque red glasses indicate that they contain high tin and iron. It is not completely clear from these analyses that copper is responsible for the colour and/or the opacification. However, a comparison with analyses using ICP techniques and SEM EDX show that these analyses are fully quantitative. [127]

Sittard

A plot of relative levels of Pb and Sn in all analysed glass from Borgharen and Sittard using p-XRF shows very similar patterns for both sets of beads.[128] These data for Sittard, in particular, have a strong positive correlation. The beads from Sittard contain Sn levels of between 3% and 12.5%. Such high levels must be due to a high density of $Pb_2Sn_2O_7$ crystals in the glasses – analysis of the matrix glass between the crystals using ED-XRF would likely produce a lower level of Sn in the matrix. The Sittard beads contain PbO levels of between 12% and 35%. It is notable that the Borgharen data are more scattered in terms of relative Pb and Sn levels, especially at levels below 12% PbO and *c.* 3% SnO_2. The overall positive correlation between the Pb and Sn suggests that these colouring/opacifying elements were added together to the glass melt.

There is a contrast in the levels of CaO between the yellow glasses from Sittard and Borgharen,[129] with Sittard containing significantly lower levels. A majority of glasses from Sittard contain *c.* 2% CaO whereas Borgharen glasses have a peak of CaO levels at 4% so this suggests that different recipes may have been used to make the glasses at the two sites.

Discussion

'Roman' natron glass was still in circulation *c.* 800 AD, and later[130] so by examining scientifically European early medieval glass assemblages of vessels and beads it becomes possible to assess the extent to which glasses have been imported from the Middle East (whether natron or plant ash glass). Thus the scientific investigation of this technological transition also provides a way of demonstrating how local glass production developed in Europe, especially with the emergence of glass made using wood ash. Characteristic Merovingian and Carolingian vessel types were blown and bead types made in Europe from imported raw furnace glass or glass cullet in a secondary production process.

For the high lead glasses, rather than removing the PbO and recalculating the totals to 100% the use of ratios in Figs. 2.1 and 2.2 is considered to be an alternative and equally acceptable means of presenting the data so as to investigate its provenance.

All natron glasses (the majority of the analyses considered) including the base glass for opaque glasses were possibly fused in Egypt or the Levant. The natron source would have been Wadi el Natrun in Egypt.

Therefore, what follows is a consideration of the provenance of the glasses and by inference also the provenance of the raw materials since local or easily accessible raw materials would have been used.

The Wijnaldum (Wij) glasses have a wide compositional range according to major (Na_2O, CaO and SiO_2) and minor components (Al_2O_3). There are three outliers (Wij 16, 17 and 32) which obscure some of the finer detail of the remaining data in Fig. 2.1. They plot as outliers because Wij 16 contains a very high CaO level (11.7%), Wij 17 is probably not a glass and Wij 32 is a plant ash glass (5.5% MgO and 2.2% K_2O) rather than a natron glass. Wij 37 has a very unusual composition. It is possibly a plant ash glass, but contains 9.7% Al_2O_3 and 3.7% Na_2O.

Therefore in Fig. 2.1 the data for Wij 16, 17, 32 and 37 have not been included. This allows for a more sensible comparison between the results for glass from other early medieval Dutch sites as well as other selected contemporary sites. This plot is an approximate way of defining compositional types and potential for raw material provenance used by other researchers.[131] The plot suggests that Wij 1, 2, 3, 9, 13, 18, 20, 23, 25, 30, and 31 are potentially Levantine glasses (though see Chapter 5) and that Wij 24 is of the HIMT type and therefore potentially made in Egypt.

The main bulk of early medieval Dutch natron glass fall into the Foy 2 compositional types (and its variants).[132] These glasses have undergone

127 Personal comment Hans Huisman.
128 Huisman *et al.* 2019.
129 Van Os *et al.* 2014.
130 Phelps *et al.* 2016.
131 Bertini, Henderson & Chenery 2020.
132 Foy *et al.* 2003; Ceglia *et al.* 2015; 2019; Schibille, Sterrett-Krause & Freestone 2016; Bertini, Henderson & Chenery 2020.

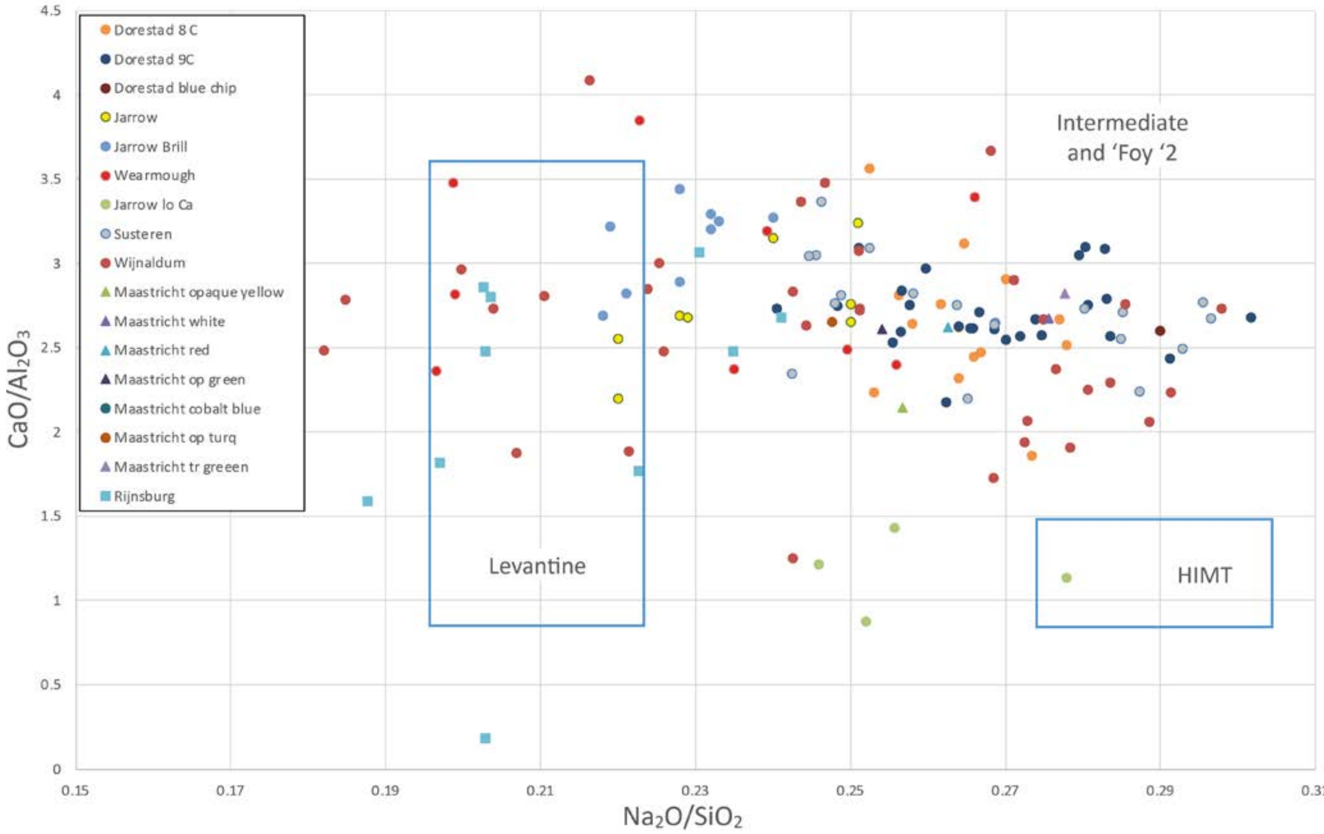


Fig 2.1 A plot of Na_2O/SiO_2 versus CaO/Al_2O_3 in early medieval glass beads and vessels compared to glasses from Jarrow and Monkwearmouth, UK (Brill 2006; Freestone & Hughes 2006).

multiple recycling/mixing episodes. Even if they were originally pristine Egyptian glasses before they were mixed their provenance cannot now be identified exactly. The glasses typically contain elevated Fe_2O_3, TiO_2, MnO and also some elevated MgO, P_2O_5 and K_2O.

The plotted points for the mean results of both translucent and opaque glasses from Maastricht all fall within the area that coincides with the intermediate/'Foy 2' glasses. This is to be expected given some of their other compositional characteristics discussed above, including quite high MgO, MnO, and Fe_2O_3 and therefore come into consideration for HIMT or related glasses. None of the glasses contain high TiO_2 levels. A single translucent blue chip of glass appears to have a pristine Levantine composition: with a Na_2O/SiO_2 ratio of 0.14 it falls well below other glasses considered here – due to its 74% SiO_2 – and can therefore be tentatively suggested as a product of Bet Eli'ezer characterized by such high SiO_2 levels[133] although its Al_2O_3 level of 2.4% is *c.* 0.5% lower than would be expected.

Fig. 2.2 should be a more precise way of defining different compositional types of natron glasses. There are five outliers: Wij 11, 13, 14, 15 and 33. The reason why these are outliers is that they contain high levels of iron: blue-green no. 11 (2.2%), opaque red no. 13 (4.6%), opaque red no. 14 (4.1%), opaque red no. 15 (4.4%) and dark olive green no. 33 (3.2%).

Without plotting the outliers in Fig. 2.2 a better classification of Wijnaldum glasses than seen in Fig. 2.1 becomes evident. By far the largest proportion of samples fall into the same 'intermediate'/'Foy 2' composition as seen in Fig. 2.1. None of the Wijnaldum glasses fall below the Fe/Ti value of 0.5, a value that may be technologically significant for the few Susteren and Dorestad intermediate/'Foy 2' glasses that do. The low values of Fe/Al of <0.2 for four Wijnaldum glasses (numbers 1, 9, 30 and 31) could suggest that they are unrecycled Levantine glasses, but see Chapter 5.

Wijnaldum 1 could potentially be of a Levantine–Apollonia type[134] and Wijnaldum 30 perhaps of the Levantine–Jalame type.[135]

133 Freestone, Gorin-Rosen & Hughes 2000.
134 Phelps *et al.* 2016.
135 Gallo *et al.* 2015.

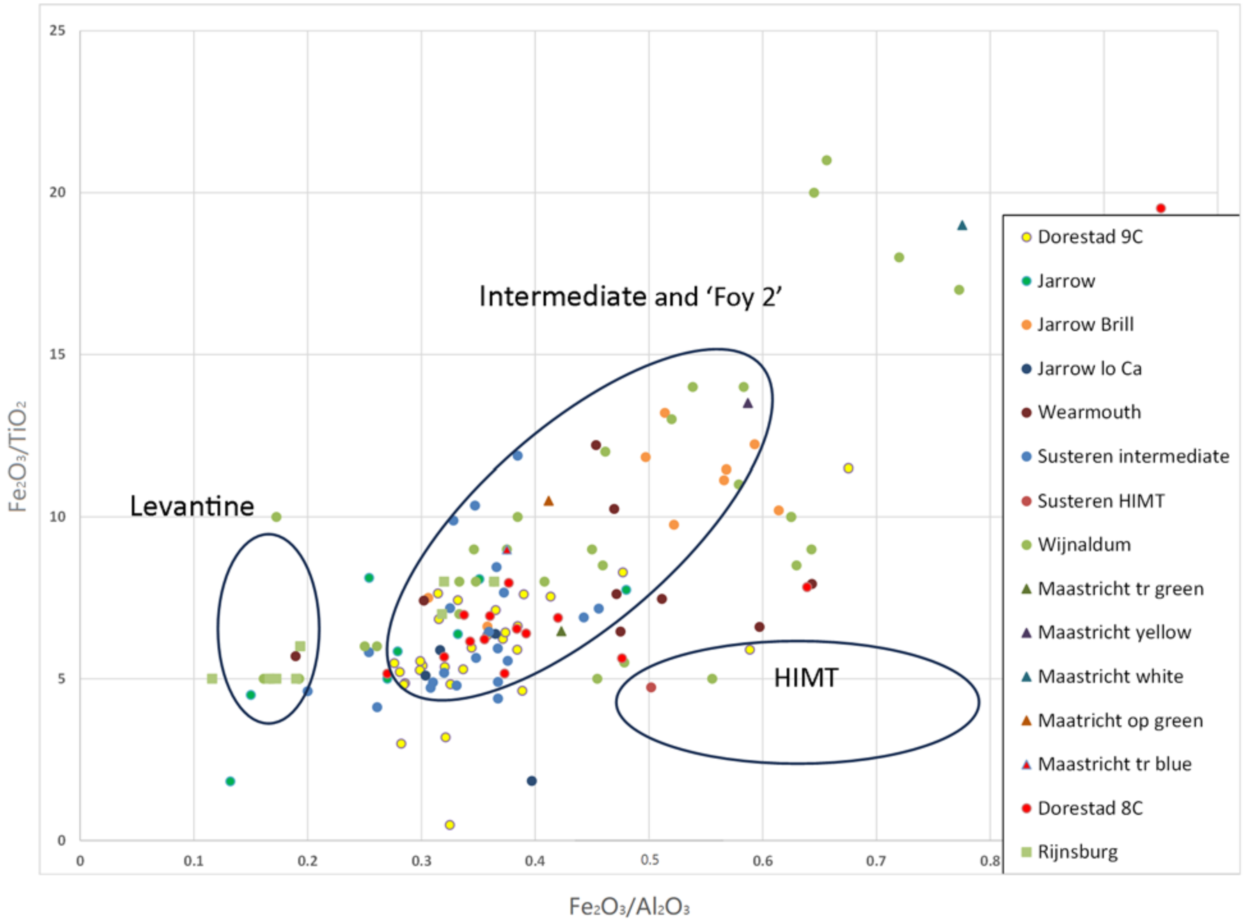


Fig 2.2 A plot of Fe_2O_3/Al2O3 versus Fe_2O_3/TiO_2 in Dutch early medieval glass beads and vessels compared with results from Jarrow and Monkwearmouth UK (Brill 2006; Freestone & Hughes 2006).

These glasses are characterized by low MgO and K_2O at *c.* 0.5%–0.7% weight, Al_2O_3 *c.* 3%, and low iron and titanium. Overall, they lack the elevated MgO, K_2O, TiO_2, Fe_2O_3 and MnO (and sometimes P_2O_5) that characterize 'Foy' glasses, found in the bulk of the remaining data. However a more detailed interpretation is given in Chapter 5.

Three Wijnaldum glasses, 5, 7 and 12, appear to plot with HIMT (high iron, manganese and titanium) glasses in Fig. 2.2. Careful evaluation of the results indicates that glasses 5 and 7 are unlikely to be HIMT, glass 12 is more typical of the composition (i.e. it contains 0.3% TiO_2). The difficulties in allocating a glass type to these natron glasses are overcome significantly by analysing them with the more sensitive technique, laser ablation inductively coupled plasma-mass spectrometry (LAICP-MS): see Chapter 4.

Maastricht mean results are plotted in Fig. 2.2 (triangles). All of the glasses, irrespective of whether they are translucent or opaque, fall into the area of the plot occupied by 'transitional'/'Foy 2' glasses. This suggests provisionally that all the glasses analysed from the site are recycled/mixed and therefore conform to the bulk of other analyses of early medieval glasses from the Netherlands using the relative values of Na_2O/SiO_2 and CaO/Al_2O_3. None fall into the area of the plot occupied by pristine Levantine natron glasses or HIMT glasses. See Chapter 5 for a more detailed consideration.

Although it was suggested above that the translucent blue chip of glass from Maastricht might be a pristine Levantine glass, when plotted in Fig. 2.2 this appears not to be the case. As noted above most have elevated MgO, MnO and Fe_2O_3 concentrations, above the values found in pristine Levantine glasses (and pristine Egyptian HIMT glasses); trace element analysis (Chapter 5) reveals a more definitive means of classifying the glass. Early medieval opaque and translucent glasses have not been considered together before in this way. This initial evidence therefore suggests that recycled/mixed early medieval glass was used as a base glass for adding opacifying compounds – and this is also apparently true for the single translucent blue glass sample from Maastricht. Due to the high level of contamination of both translucent glasses in the crucible fragments from Maastricht the results have not been included in Fig. 2.2.

The Susteren glasses plot with 8th and 9th century Dorestad glass having Na/Si oxide ratios of above 0.24. Nevertheless, Levantine glasses can also plot within the area occupied by glasses with 'Foy 2' and 'intermediate' compositions[136] so as noted above a better discrimination is needed; an attempt at this is given in Fig. 2.2. It appears that none of the Susteren glasses are pristine (unrecycled) Levantine I, Levantine II[137] or N1 Levantine glasses as defined by Kato *et al.*[138] which are manufactured at primary production sites. The compositions for glass beads 1 and 6 as well as vessels 21, 23, 24 and 27 from Susteren are possible contenders for Levantine glasses but all contain higher levels of MgO, P_2O_5, K_2O, TiO_2, MnO and Fe_2O_3 than pristine natron glasses. This is also true of all other natron glasses from the site. These elevated levels of impurities show that almost all of the Susteren natron glasses have been recycled, perhaps several times.

A nearly colourless funnel beaker from Susteren with a dark blue *incalmo* rim (no. 26) is the only example of an HIMT composition. It has the highest Fe_2O_3 (1.34%), TiO_2 (0.4%) and MnO (1.79%) levels of all the Susteren samples. It also contains a low calcium oxide level of 6.2%, another characteristic of HIMT glass. All other Susteren natron glass is of the 'intermediate'/'Foy 2' type with higher calcium oxide and elevated levels of MgO, P_2O_5, K_2O, TiO_2, MnO and Fe_2O_3 compared to pristine Levantine I and other natron glasses.
The Susteren glass plots close to Jalame (Levantine I) on a major/minor component plot of Na/Si oxides versus Ca/Al oxides with relatively high Na/Si oxide values of above 0.24. However it is clear that when sand impurities are plotted in Fig. 2.2 apart from the HIMT sample they fall into the same plotted area as 'Foy 2' compositions as defined by Ceglia *et al.*[139] and Schibille *et al.*[140] and 'intermediate' glasses from Comacchio as defined by Bertini and colleagues.[141]

In Fig. 2.1 Dorestad '8th' century (pre-750) glasses are plotted separately from Dorestad '9th' century (750–850 AD) glasses. Almost all '8th' century glasses have CaO/Al_2O_3 values of between 2.5 and 3.09 or close to this range, whereas '9th' century (750–850 AD) glasses have a far wider range of such values, of between 1.86 and 3.5. This suggests that raw materials with a wider compositional range were used and/or that mixing/recycling introduced a wider compositional range in the glasses that date to before 750. On this basis all Dorestad glasses can be classified as 'intermediate'/'Foy 2'.

Figure 2.2 (from which Dorestad outliers have been removed) on the other hand provides further interesting insights into the Dorestad glasses. Almost all natron glasses are of the 'intermediate'/'Foy 2' composition according to this plot. However, four Dorestad glasses have low Fe/Ti oxide values of between 0.48 and 4.63 and this distinguishes them from the vast majority of early medieval European 'intermediate'/'Foy 2' glass and extends the values of such glass. All '8th' century Dorestad glasses have Fe/Ti ratios of above 5. This increasingly wide range of Fe/Ti oxide values in early medieval European glass deserves to be revisited in more detail using trace element analysis. The single Dorestad glass that plots in the 'HIMT' area is in fact a plant ash glass with low Al_2O_3 (1.9%). This however raises the issue of whether the silica sources used to make plant ash glasses would benefit from such an approach. Other trace element ratios have been used to investigate Islamic plant ash glasses,[142] as have radiogenic isotopes.[143]

Rijnsburg glass tends to have lower Na/Si oxide values than most translucent early medieval glass (Fig. 2.1) which is intriguing because it suggests that the base glass could be pristine (unrecycled) Levantine glass, though this would still need to be confirmed with trace element analysis. If this is the case it would show that relatively pure glass was imported and used as the base glass for making the opaque Rijnsburg material. Three glasses with Na/Si values above 2.2 are (based on Fig. 2.1) probably of an 'intermediate'/Foy composition.

As can be seen in Fig. 2.2 six Rijnsburg glasses plot in the area of Fe/Al versus Fe/Ti oxide values that is consistent with being pristine Levantine glasses too, so this substantiates the above suggestion. As noted above the use of ratios allows a direct comparison with translucent glasses even though the opaque glasses contain high levels of PbO

136 Bertini, Henderson & Chenery 2020.
137 Freestone, Gorin-Rosen & Hughes 2000.
138 Kato, Nakai & Shindo 2009.
139 Ceglia *et al.* 2015.
140 Schibille, Sterrett-Krause & Freestone 2016.
141 Bertini, Henderson & Chenery 2020.
142 Henderson *et al.* 2016.
143 Henderson, Ma & Evans 2020.

and Sn. This is an unexpected and intriguing result which indicates how important further research using trace element and isotopic analysis would be.

The two Rijnsburg glasses that have been badly contaminated when being worked, as well as the material attached to the Rijnsburg crucible, and glasses with very high Fe levels have not been included because, for different reasons, they cannot be compared with the other plotted glasses with any validity.

It is impossible to plot Lent data on Fig. 2.1 because no soda was quoted. An attempt to plot the data for Lent in Fig. 2.2 was made and, where data was available, all plotted well away from the other data. This suggests that the quality of the data is too low to be considered further here.

A small number of early Islamic plant ash glasses were used to make early medieval beads and vessels. The glasses have elevated MgO and K_2O concentrations and are quite distinct from natron glasses as discussed above. A plot of MgO versus CaO in relation to Levantine, northern Syrian and Iraqi/Iranian early Islamic glasses (not given here)[144] suggests that glasses from Wijnaldum and Susteren ultimately derive from Iraq or Iran, that a second glass from Susteren probably derives from Syria and a single glass from Dorestad probably derives from the Levant. Their provenances using trace element analysis are discussed in more detail in Chapter 5.

As already discussed, the bulk of Dutch early medieval glasses are of the 'intermediate'/'Foy 2' composition. Given the range of impurities in these glasses they have undergone potentially multiple episodes of recycling and mixing. Most glasses of these highly variable compositions date to, at the earliest, the 8th century and, using major and minor chemical analysis, there is no clear development or change in their chemical compositions over time.

However, a number of observations can be made when the compositions of glass from different early medieval sites are compared. Both Rijnsburg and Wijnaldum glasses appear to include more examples of imported pristine glass than the later sites of Susteren and Dorestad. At Rijnsburg such glass would have been used as the base glass for making beads. However, currently there is no actual evidence for mixing colourants with pristine glass there. Based on these results no pristine glass was detected at Susteren or Dorestad and only a single probable example has been detected amongst the Maastricht glass. This suggests that there may have been a more direct supply of pristine glass *c.* 600 AD to some sites where the glasses were coloured/opacified (and possibly made into beads or vessels on the same sites) than for the Foy 2 glasses where a number of recycling events would probably indicate that more intermediate sites were involved.

Moreover, the variation in composition of natron glasses as defined by major oxides (Na_2O, SiO_2, CaO) as well as Al_2O_3 appears to decrease with time when glasses dating to before *c.* 750 AD ('8th century' in Fig. 2.1) are compared with those that date to after *c.* 750 AD ('9th century' in Fig. 2.1). All of these observations would benefit from further scientific analyses using more sensitive techniques of chemical analysis and also isotopic analysis (see Chapter 5).

Matthes[145] has suggested that there was an increase in the levels of As and Sb in opaque yellow glass over time from *c.* 600 AD. The implication could be that the lead sources changed over time. However significant levels of As have not been detected in Dutch early medieval opaque yellow glass using electron microprobe analysis and the increase in Sb levels might relate to increasing levels over time in the base glass used (see Chapter 5).

Early Islamic plant ash glass was introduced in the early 9th century so we can be sure that these few early medieval examples date to this time, or later. Further analyses of early medieval Dutch glasses will certainly reveal more examples and it may eventually be possible to suggest the key centres that such glasses and glass artefacts were imported from.

Based on this provisional review we can suggest that glass used to make early medieval vessel, bead and window glass found in north-western Europe was mainly imported and reworked there. Primary production for natron glass occurred in the Levant and Egypt where coastal sand and natron from Wadi el Natrun were fused in large tank furnaces. Glass furnaces have been found on a number of early medieval northwestern European sites but all of these show evidence of secondary production (glass working). It is conceivable that glass was reheated and blown into characteristic early medieval vessel types such as bowls and beakers or made

144 Henderson *et al.* 2016.
145 Matthes 1998, fig. 10.

into beads and windows; the weight of evidence suggests vessels were made in Germany.
The exceptions are the production of an opaque yellow material (originally suggested to be glass), especially at Maastricht and, later, when the first wood ash glass was made from about 800 AD. It is possible that mixed-alkali glass was made at Méru by adding wood ash to natron glass but a more likely technique was to mix the two types of glasses.

Although most early medieval northwestern European glass is natron glass only small numbers of pristine (unrecycled) Levantine and Egyptian glass occur. Most glass that has been found dating to between the 4th and 10th centuries is HIMT (characterized by high levels of iron, manganese, titanium and zirconium) and its recycled variants. Based solely on the major and minor elemental analysis of early medieval Dutch natron glass, most appear to fall into the recycled Foy 2 compositional types.[146] These Dutch early medieval glasses typically contain elevated Fe_2O_3, TiO_2, MnO and also some elevated MgO, P_2O_5 and K_2O.[147] A much more detailed consideration of the probable origins of early medieval Dutch glass using trace element analysis is given in Chapter 5 of this book.

Concluding remark

Glass from the earlier periods, between 450–550 and 550–650 AD contain somewhat more examples of unrecycled ('pristine') glasses and a smaller number of recycled glasses. By the time of the Carolingian empire from about 750 AD almost all the glass is recycled as exemplified by glass found at Dorestad. Exceptions are Egyptian II glass from Hedeby and Cologne. By 800 AD primary glass production of wood ash glass occurs in northwestern Europe and, as noted above, at a time of technological transition, the production of mixed-alkali glasses occurred. Plant ash glass was imported from western Asia in the form of beads and raw glass; it was used in the manufacture of early medieval European beads and occasionally glass vessels.

146 Foy 2003; Ceglia *et al.* 2015; 2019; Schibille, Sterrett-Krause & Freestone 2016; Bertini, Henderson & Chenery 2020.
147 Henderson 2012; Henderson 2023.

3 Evidence for early medieval glass-working in the Netherlands

3.1 Introduction

Glass production can be divided into two different stages. The first is primary production involving the fusion of raw materials (see Chapter 2). The second is remelting the glass made in the first stage to make glass objects. There is no recorded evidence for primary glass production in the early medieval Netherlands. There is, however, evidence for secondary production, not just the remelting of glass but also the manufacture of pigments for glass coloration.

In the Merovingian period, comprehensive evidence for glass bead making has been found at Maastricht-Jodenstraat, Rijnsburg-Abdijterrein and Wijnaldum (fig. 3.1). The evidence falls between the last quarter of the 6th and first half of the 7th century. As Pion has shown, this period coincides with a steep reduction of imported oriental beads in the west, giving birth to a new production of highly coloured Merovingian bead types.[148] Maastricht, developed from an old Roman town was one of several production centres in the middle Meuse valley[149], well within the borders of the Merovingian empire. On the other hand, the production of popular Merovingian bead types in the central places[150] of Rijnsburg in the Rhine delta and the northern terp site of Wijnaldum shows that the demand for fashionable beads reached well beyond the borders of the Merovingian empire (fig. 3.1).

There is scantier evidence for glass production in the Carolingian period in the form of waste, perhaps in part because the custom of wearing colourful beads became less popular in the Frankish heartlands[151], though they were still being worn in the northern periphery of the Carolingian empire. Imports of Islamic period beads from the end of the 8th century onwards[152] in settlements along the Rhine and in cemeteries north of the Rhine, traded through Viking trade networks to the west, may also have contributed to a reduction in Frankish glass bead production. Another notable difference with the preceding period is that that the evidence for glass working derives from a more varied range of site types and now includes an early emporium (Dorestad) and ecclesiastical centres (Utrecht-Domplein, Susteren) (fig. 3.1). From the Carolingian period, not all phases of the production processes are represented by the glass working waste, so it is more difficult to attribute what evidence there is to specific products. Glass beads were probably made at Dorestad, while possible evidence for the production of the earliest highly coloured stained window glass was found at the early medieval monastery of Susteren.

In the following the sites are considered starting with southern sites and moving northwards.

Fig. 3.1 Sites in the Netherlands with evidence for glass working in the early medieval period (adapted from Dijkstra 2011, 12).

148 Pion 2014.
149 Van Wersch 2012.
150 Nicolay 2017.
151 Delvaux 2017.
152 Sablerolles & Van der Linde-Louvenberg 2019 (Leiderdorp-Plantage); Langbroek 2021b (Dorestad); Van Es & Schoen 2007/2008 (Zweeloo cemetery).

3.2 Maastricht, Limburg Province

Excavations carried out in Maastricht in the 1980s and early 1990s yielded evidence of an impressive range of craft activities carried out during the 6th and 7th centuries. The location of Maastricht is shown in fig. 3.1. In total, nine different sites were identified in quite different parts of the settlement.[153] Apart from one, these were all located on the west bank of the Meuse. Here a Roman castellum had been constructed in the 4th century which developed into an important political, religious and economic centre in the Middle Meuse region during the Merovingian period. Maastricht had its own bishop, see and mint. Gold coins minted in Maastricht have been found all over north-western Europe, with a significant concentration in the northern Netherlands, especially in Friesland Province.[154]

Evidence of glass-working was found at six locations, the Mabro site (Onze Lieve Vrouweplein), the Derlon site, the Jodenstraat site, the Rijksarchief site, the Boschstraat area and the Lage Kanaaldijk site.[155] On all of these sites glass-working was combined with one or two other high-temperature crafts (table 3.1), namely pottery production (Lage Kanaaldijk), iron-working (Boschstraat, Rijksarchief), copper-alloy working (Derlon, Boschstraat, Jodenstraat) and possible gold-working (Mabro). Antler-working took place at the Mabro site, Derlon site, Boschstraat area and Rijksarchief site, while waste from amber-working was mixed in with glass bead production waste from the Jodenstraat site.

It is likely that glassworkers worked closely with other craftsmen and shared knowledge about furnace technology, fuel and other materials. For instance, the glass crucibles used by the glassworkers on the Jodenstraat, Mabro and Rijksarchief sites were all repurposed ovoid coarse-ware cooking pots (*Wölbwandtöpfe*) which were most probably made in Maastricht. At the Céramique site on the east bank of the river Meuse, four cross-draught kilns were found filled with wasters, dominated by coarse-ware *Wölbwandtöpfe* (fig. 3.2).[156] Remarkably, these pots are also used as glass crucibles in Merovingian Rijnsburg (see Section 3.8) and Valkenburg-De Woerd (see Section 3.9) and there is continuity in the reuse of *Wölbwandtöpfe* as glass crucibles into the Carolingian period (globular pots type Dorestad W III) (see discussion by Menno Dijkstra, Section 3.5.1)

Fig. 3.2 Maastricht-Céramique site: A restored cooking pot (*Wölbwandtopf*) from the fill of a furnace (Photograph: Wim Dijkman).

Table 3.1 Maastricht: Early medieval sites with evidence for glass-working in combination with other crafts.

Maastricht sites	High-temperature crafts					Other crafts	
	glass	pottery	iron	copper-alloy	gold?	antler	amber
Derlon	X			X		X	
Mabro	X				X	X	
Jodenstraat	X			X			X
Boschstraat area	X		X	X		X	
Rijksarchief	X		X			X	
Lage Kanaaldijk	X	X					

[153] Dijkman 2013.
[154] Pol 1999, fig. 7.
[155] Sablerolles, Henderson & Dijkman 1997, 295, fig. 1; Dijkman 2013, fig. 1.
[156] Dijkman 2013, fig. 4.

3.2.1 Maastricht-Jodenstraat (MAJO)

Site: 1
Site type: specialist craft zone
Province: Limburg
Municipality: Maastricht
Place: Maastricht
Toponym: Jodenstraat 30
Start date 580/590 (late 6th century)
End date: 610/620 (early 7th century)
Description: In 1988 excavations by the Gemeentelijk Oudheidkundig Bodemonderzoek Maastricht (GOBM), the Municipal Archaeological Service of Maastricht, took place at Jodenstraat 30.[157] The site was situated north of the late Roman castellum, near the *Via Belgica* which connected Tongeren and Maastricht.
A rubbish pit filled with the debris from glass bead making was found.[158] The pit also contained waste from copper-alloy-working and amber-working.[159] Based on the pottery finds, the pit was filled sometime in the late 6th to early 7th century. To date, the glass assemblage represents the most comprehensive evidence for 6th–7th century glass bead making in Europe.

Glass production waste: The debris consisted of 750 glass objects which represent the full range of waste from glass bead production.
The production waste was divided into eight main groups: glass rods (n=369), 'punty' glass from a beadmaker's tool (n=36), glass threads with and without tweezer marks (n=17), glass drops (n=39), finished and failed beads (n=123), crucibles (n=38, EMN=17), cullet or scrap glass (n=20), glassy slags/fuel ash slags (n=53) and non-diagnostic fragments (n=55) which include (small lumps of) melted glass and fragments that are too small to classify. All waste categories are dominated by opaque yellow glass (apart from scrap glass and glassy slags). Opaque yellow, green, red, white, red and blue make up 57%, 17%, 16%, 7% and 0.9% of colours respectively. The balance are translucent light green (2%) and blue-green (0.6%), and transparent colourless (0.2%) of glass.

Almost all beads are wound and have tapering perforations showing they were made by winding melted glass around a mandrel, a bead-making tool with a conical point. Such a tool may have been found at the Rijksarchief site (see Section 3.2.3). A few beads were made by perforating a section of a 'composite' glass rod which was made by fusing strands or slender

Fig. 3.3 Maastricht-Jodenstraat site: From left to right: opaque yellow melted rods ends and threads with tweezer marks, finished pentagonal beads, drawn and composite rods, failed, cracked beads (Photograph: Gemeentelijk Oudheidkundig Bodemonderzoek Maastricht (GOBM)).

157 The site remains unpublished, apart from the rubbish pit with production waste.
158 Sablerolles, Henderson & Dijkman 1997.
159 For waste from amber-working, see Dijkman 2013.

rods together in order to make a glass rod with a large enough diameter for making a bead. The vast majority of the beads (79%) are cylindrical in shape, predominantly with a pentagonal section (76%), while some have a square (2%) or round (1%) section. The polygonal beads were believed to have been shaped with tongs but are much more likely to have been shaped by hand with a small wooden tool known as a paddle. The remainder of the beads are made up of small globular beads of opaque yellow glass and medium-sized bi-conical beads. The majority of the beads are split in half along the length of the perforation (72%) (fig. 3.3). This is a commonly observed phenomenon on bead-making sites (see Section 3.8 and Section 3.12) and occurs when the glass is overheated during the making of the beads, or when the beads have not been annealed or cooled down properly, causing the beads to crack.[160]

Crucibles are represented by 38 fragments from at least 17 coarse-ware cooking pots (*Wölbwandtöpfe*). In 15 cases, only the lower halves of the pots were used to melt what was originally believed to be highly coloured opaque yellow glass (see Section 5.2.3). More recently, a crucible base with an opaque white deposit was identified by one of the authors of the 1997 publication (fig. 3.4).[161] Table 4.2 lists further selected crucibles and associated glassworking debris from Jodenstraat (MAJO 1-27); images are in Appendix IV (figures appendix IV.11-38). No crucibles with opaque red, green and blue glass have been found.

Once made, opaque glass would have been worked into beads, for instance by gathering some melted glass onto a solid metal rod or punty and winding it around a mandrel, a bead-making tool with a conical point. However, the presence of opaque yellow and white glass rods suggests that these were an essential phase in the bead-making process.

The rods were made by attaching two metal rods (punties) to a gather of melted glass, then pulling the glass in opposite directions creating a drawn glass rod of several metres' length with a more or less round cross-section The long glass rods could have been fragmented into shorter sections, as suggested by the presence of a particular type of glass rod breaking splinter. Short rod sections could have been pre-heated, picked up with a punty, as indicated by the presence of punty glass among the waste products, and wound around a mandrel.[162] Alternatively, a production technique in use by modern beadmakers may have been used.

Fig. 3.4 Maastricht-Jodenstraat site: Crucible base with opaque white glass, drawn and twisted opaque white rods and cracked, failed beads (Photograph: Gemeentelijk Oudheidkundig Bodemonderzoek Maastricht (GOBM)).

160 Gam 1990; Heaser 2018.
161 Dijkman 2013.
162 Cf. Sode 2004; Risom 2013, 56–57, 60.

Table 3.2 Maastricht, Jodenstraat (MAJO): selected artefacts and photo numbers.

Find number	Fragment	Glass colour(s)	Sample	Sample number	Photo number
1-1-7-4	crucible base	opaque yellow	MAJO 1	20	figure appendix IV.11
1-1-5-17	crucible body	deep translucent and yellow	MAJO 2	21	figure appendix IV.12
1-1-7-11	crucible base	opaque yellow	MAJO 3	22	figure appendix IV.13
1-1-7-3	crucible base	opaque yellow	MAJO 4	23	figure appendix IV.14
1-1-7-2	crucible base	opaque yellow	MAJO 5 (inside) & MAJO 5 (outside)	24	figure appendix IV.15 (inside) & figure appendix IV.16 (outside)
1-1-7-8a	crucible base	opaque yellow	MAJO 6	25	figure appendix IV.17
1-1-7-8b	crucible base	opaque yellow	MAJO 7	26	figure appendix IV.18
1-1-7-8c	crucible base	dark translucent	MAJO 8	29	figure appendix IV.19
1-2-3	possible brick fragment	white and opaque yellow	MAJO 9	30	figure appendix IV.20
1-1-7-451 a and b	fragments	blue	MAJO 10	39-40	figure appendix IV.21
1-1-7-21-22a	scrap	red	MAJO 11	41	figure appendix IV.22
1-1-7-21-22b	scrap	red	MAJO 12	42	figure appendix IV.23
1-17-28	scrap	green	MAJO 13	43	figure appendix IV.24
1-2-3-VG3-2	window	yellow-green	MAJO 14	44	figure appendix IV.25
1-2-3-VG3-1	window	yellow-green	MAJO 15	45	figure appendix IV.26
1-2-3-VG3-3	window	pale yellow-green	MAJO 16	46	figure appendix IV.27
1-1-7-500	thin rod	green	MAJO 17	47	figure appendix IV.28
1-1-7-431	drop	yellow weathered	MAJO 18	50	figure appendix IV.29
1-1-5-388	drop	red	MAJO 19	51	figure appendix IV.30
1-1-7-463	drop	dark green	MAJO 20	52	figure appendix IV.31
1-1-7-462	pulled rod	milky blue	MAJO 21	53	figure appendix IV.32
1-1-7-583-594	thin rod	red	MAJO 22	54	figure appendix IV.33
296	twisted rod	opaque white	MAJO 23	58	figure appendix IV.34
1-2-5a	beaker base	green	MAJO 24	60	figure appendix IV.35
1-2-5-b	punty glass	blue	MAJO 25	61	figure appendix IV.36
1-1-7-503	ribbed flat	blue-green	MAJO 26	68	figure appendix IV.37
309-349	rod fragments	green	MAJO 27	73-74	figure appendix IV.38

This involves heating up the end of a longer section of a glass rod, attaching the hot glass to a mandrel and winding it directly around a mandrel.

According to experimental glass beadmaker Sue Heaser, finds of glass rods of about 5–10 mm thick on many early medieval bead-making sites suggest that that beadmakers in the first millennium AD knew the technique.[163] She states that this method gives more control than using a gather of molten glass attached to a punty. She goes on to explain that only the end of the glass rod is heated to liquid point so that the rest of the rod remains cool and rigid. The cool end is used as a handle by the beadmaker to control the hot glass at the other end as it is applied to the mandrel. This could be another explanation for the presence of 'composite' glass rods at the Jodenstraat site made up of lots of strands or slender rods which are fused or twisted together (fig. 3.3 and fig. 3.4). Modern beadmakers use these leftover bits to fuse onto the end of glass rods when they have become too short to handle.[164] Several examples of rods with melted ends (fig. 3.3) among the waste material from the pit could have been destined for this kind of recycling by melting the ends and pressing two of the same colours together.[165]

Chemical analyses published in 1997 suggested that the lead-tin-yellow crucible residues has the same composition as the opaque yellow glass rods and other waste

[163] Heaser 2018.
[164] Personal comment Ingrid Pears, Hot Glass Studio, Thoresby, Notts., UK.
[165] Cf. Heaser 2018.

products, including (failed) beads. Moreover, the chemical compositions of opaque white, red and blue-green glass rods was also linked to waste products of corresponding colours. However, only trace analysis can give incontrovertible evidence that this is indeed the case (see Section 4.4). No crucibles fragments bearing opaque red, blue-green or blue glass were found and it was believed that these must have been imported in the form of glass rods that were directly worked into beads. In that case, the base glass used for the presumedly imported glass colours is likely to be different from the base glass used for the locally made opaque yellow and white glasses. A more detailed scientific investigation looking into this matter is given in Chapter 5.

Fragments of the rim, (upper) bodies and base of two crucibles show that complete pots were used to melt colourless glass and translucent blue-green glass. Drops of translucent greenish glass amongst the waste products suggest this glass was worked on or near the site (fig. 3.5). Fragments of translucent greenish scrap glass – old vessel glass and the earliest early medieval grozed window glass from the Netherlands – were interpreted as cullet destined to be remelted to create this type of base glass. Further detailed investigations of the base and scrap glass using trace element analysis are given in Chapter 5.

Not included in the 1997 publication are a couple of fragments of Roman faience melon beads and a handful of very small fragments of crushed translucent dark blue glass (fig. 3.5) as well as an almond-shaped bead of translucent dark blue glass. Although it is impossible to establish from what kind of object(s) the translucent blue crushed fragments come from, it is tempting to suggest they could derive from early plano-convex glass 'cakes' of translucent dark blue glass which are found on later 8th–9th century bead-making sites in southern Scandinavia, such as Åhus (Sweden)[166] and Ribe (Denmark)[167] and at Dorestad[168] (see Section 3.4.2). With this in mind, it will be interesting to see whether the translucent dark blue crushed fragments can be chemically linked to a translucent dark blue bead found among the waste. Moreover, could this translucent dark blue glass have been used as a base glass to make opaque blue glass on site given there are three beads and a drop of opaque blue glass as well as an opaque greyish blue glass rod. This will be further discussed in Chapter 5.

Fig. 3.5 Maastricht-Jodenstraat site: From left to right: fragments of Roman faience melon beads, crushed translucent dark blue glass and yellowish green window and vessel glass of translucent greenish glass with glass drops in matching colours (Photograph: Gemeentelijk Oudheidkundig Bodemonderzoek Maastricht (GOBM)).

166 Callmer & Henderson 1991, fig. 2.
167 Andersen & Sode 2010, 32, fig. 11, 34, table 11.
168 Preiß 2010, nr 38, fig. 10; Sablerolles & Henderson 2012, afb. 6.19, NO 5041.

3.2.2 Maastricht-Mabro

Site: 2
Site type: dump zone
Province: Limburg
Municipality: Maastricht
Place: Maastricht
Toponym: Mabro
Start date: 500 (6th century)
End date: 700 (7th century)
Description: Excavations carried out in 1981 by the GOBM or Municipal Archaeological Service of Maastricht at the site of the Maastrichtse Broodfabriek (Mabro) or the Maastricht Bread Factory, located at the Onze Lieve Vrouweplein (MAVP) 16–18 remain unpublished.
Glass production waste: The site produced twelve fragments of glass crucibles, a substantial number of beads, glassy slags, one of which might be a fragment of melted furnace wall, and at least one red-burnt fragment of clay covered with translucent greenish glass.[169]

Eleven crucible fragments can be dated to the 6th or 7th centuries (*Wölbwandtöpfe*), of which ten were made available for sampling (table 3.3). Additionally, one rim fragment (find no. 1-5-OA) is of a late 4th–early 5th century bowl (type Alzey), perhaps recovered from a late Roman grave and reused in the Merovingian period. Chemical analysis of the latter was included in the 1997 Maastricht-Jodenstraat publication.[170]
The fragment is covered with translucent greenish glass below the rim and a vitrified, off-white granular material on the inside and outside of the rim. At the time, this was tentatively interpreted as overheated frit. Frit is a half-product of glass-making, so this could constitute the earliest evidence of glass-making in the early medieval west. This material has now been re-analysed using scanning electron microscopy and the results are presented in Section 5.2.

Two rim fragments of Merovingian crucibles show similar deposits (table 3.3). As is the case on the Jodenstraat site, the crucibles either contain colourless or translucent natural green glass or opaque yellow glass; no crucible fragments with other colours were found.

Table 3.3 lists ten crucible fragments together with selected images (MABRO 1-10) from Maasricht-Mabro and the sample numbers used in scientific analysis. The images are at Appendix IV (figures appendix IV.1-10).

Judging from photographs of the beads, they are all made by winding and are either monochrome or decorated with trails in contrasting colours.[171] Using the bead typology developed by Pion in 2014 for beads from six Merovingian cemeteries in Belgium, later adapted by Vrielynck, Mathis and Pion,[172] the Mabro beads cover a long period between 480–530 (P1) and 620–670 (P_5), but they mostly date in period 560–610 (P_3) and period 610–640 (P_4) (table 3.4).

This site has not been published, so it is impossible to state which beads are likely to be local products, but given the dates for the crucibles, those beads dating to roughly the

Table 3.3 Maastricht-Mabro: Selected crucibles and their glassy contents, together with photo numbers and sample numbers.

Find number	Fragment	Glass colour(s)	Sample	Photo number
03-04-2000	rim	white: frit-like	MABRO 1	figure appendix IV.1
3-OA-55	body	colourless/white: frit-like	MABRO 2	figure appendix IV.2
01-03-1951	body?	translucent green	MABRO 3	figure appendix IV.3
3-OA-1	rim	colourless	MABRO 4	figure appendix IV.4
1-5-OA	rim	colourless/white: frit?	MABRO 5	figure appendix IV.5
3-OA-40 (= 3-AA-40)	base	opaque yellow	MABRO 6	figure appendix IV.6
02-02-2018	base (burnt clay?)	colourless/pale green	MABRO 7	figure appendix IV.7
03-05-2024	base	opaque yellow/green	MABRO 8	figure appendix IV.8
03-05-2024	body?	deep translucent	MABRO 9	figure appendix IV.9
03-04-2012	base	green	MABRO 10	figure appendix IV.10

169 Information and photographs of the finds were kindly provided by Wim Dijkman, Senior Conservator Archeologie en Erfgoed, Team Programma en Innovatie, Centre Céramique – Kumulus – Natuurhistorisch Museum.
170 Sablerolles, Henderson & Dijkman 1997, 307–308, pl. 25, 1.
171 With many thanks to Wim Dijkman for providing the photographs.
172 Pion 2014; Vrielynck, Mathis & Pion 2018.

Table 3.4 Maastricht-Mabro: Typology and bead periods (Pion 2014, Vrielynck, Mathis & Pion 2018).

Find number	Form	Colour	Decoration	Typology	Period
01-02-1963	globular	opaque white	translucent light blue crossing trails	B3.3-3a	P4
02-01-2000	cylindrical, round section?	opaque yellow	-	B1.4-1a?	P3?
03-04-2025	short-cylindrical	opaque red	-	B1.4-2a	P3
03-05-1932	bi-globular	opaque yellow	-	B1.2-1b	P4
03-05-1933	globular, medium	opaque white	-	B1.1-4a	P1-5
03-06-2004	globular, small	opaque yellow	-	B1.1-2a	P2-5
3-OA-0	disc	opaque white	translucent dark blue crossing trails	B3.3-2a	P3
3-OA-40.1	cube	opaque red	opaque yellow borders & crosses	B11.1-5	P2
3-OA-52	cylinder, square section	opaque red	opaque yellow dots	B6-2-1b	P5

Period: P1 = 480-530 AD; P2 = 530-560 AD; P3=560-610 AD; P4=610-640 AD and P5=620-670 AD.

2nd half of the 6th and first half of the 7th century are the most likely candidates: a small globular bead, a bi-globular bead and a possible cylindrical bead of opaque yellow glass, a medium-sized globular bead of opaque white glass and a short cylindrical bead of opaque red glass. There are two polychrome, trailed beads: an opaque white globular bead with translucent light blue narrow crossing trails and an opaque white disc-shaped bead with translucent dark blue crossing trails.

3.2.3 Maastricht-Rijksarchief

Site: 3
Site type: mixed crafts zone
Province: Limburg
Municipality: Maastricht
Place: Maastricht
Toponym: Rijksarchief
Start date: 480–490 (late 5th century)
End date: 600?
Description: Excavations carried out in 1990–1991 by the Municipal Archaeological Service of Maastricht (GOBM) are briefly discussed by Hulst.[173] The site was situated in the middle of the delta of the river Jeker, south of the 4th century Roman castellum and not far from the old Roman road which connected Tongeren, the Roman capital of the *civitas Tungrorum*, to the new centre in the region, Maastricht.

Dozens of rubbish pits were found in this area containing (late) 5th and 6th century pottery, Roman tiles, chunks of local sandstone ('*kolenzandsteen*') and flint, waste from glass-working, antler-working and iron-working. No traces of buildings were found, apart from three scattered postholes and remains of a small ditch.

Glass production waste: Hulst[174] lists 55 fragments of early Merovingian vessel glass, two glass rods, (fragments of) 25 beads, drops of glass, melted glass and small, dark vitreous spheres ('*glasbolletjes*') which may also be linked to iron-working on the site. Furthermore, one fragment of a glass crucible, glassy slags and vitrified fragments of (a) furnace floor with glassy slags and iron slags adhering to them were found. One pit contained traces of firing and may have been the firing pit of a dismantled furnace. A truly remarkable find is that of a forged iron rod which is round in section at one end and square in section at the other (fig. 3.6). Hulst remarks that the perforations of the beads match the circumferences of the iron tool. The rod is interpreted by Hulst as a bead-making tool or 'mandrel', a forged iron rod with a conical point on which beads are formed by winding a glass thread around it.

Fig. 3.6 Maastricht-Rijksarchief site: Forged iron mandrel, square-sectioned, with a round-sectioned conical point (Photograph: Wim Dijkman).

[173] Hulst 1992.
[174] Hulst 1992.

The opposite, square-sectioned end of the rod was probably originally inserted into a wooden handle.[175] A similar tool from a bead-making site at Paviken on the Baltic island of Gotland was deemed too slender for an awl and has been interpreted as a mandrel (fig. 3.7).[176] The square-sectioned end is hollow and could have been wrapped around a wooden handle. A mandrel with the remains of a handle was found at Ribe-Dommerhaven, where beads were made on a very large scale in the 8th–9th centuries.[177]

According to Hulst it is obvious that beads were made on or near this site sometime in the 6th century. He mentions that the beads are mostly made of monochrome glass, including blue, brownish-red and yellow. Some beads are decorated with glass trails of blue, white or yellow glass. The beads include finished specimens and failed beads. Among the failed beads are examples where the winding of the spiral glass trail around the mandrel had gone wrong. Cracked specimens have been found. This can occur after the glass has been overheated or when the finished beads have not been annealed properly. Both rods are monochrome opaque brownish-red.

Recent photographs of some of the finds[178] show that the scrap glass includes a thick-walled fragment of early/mid-Roman blue-green glass (probably window glass or a square bottle), a yellow-green knocked-off rim of a late Roman cup of Isings type 96a,[179] a rim fragment of a Merovingian bell beaker of yellowish-green glass with dark inclusions and lots of bubbles, decorated with vertical optic blown ribs and an opaque white trail below the straight, fire-rounded rim. The latter is probably contemporary with the bead-making. Among the beads, there is a sub-biconical opaque red bead with an opaque yellow spiral. This is the only specimen which can be securely dated to Pion's Period 3 (560–610 AD), while a seemingly dark/dirty bi-globular bead with whitish deposits is probably of Pion's Period 4 (610–640 AD).[180] A spiral bead of translucent light greenish glass is very similar to one found at Leidsche-Rijn Leeuwesteyn Noord (Rijnfront) (see Section 3.6.2).

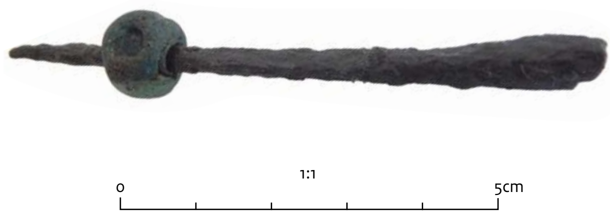


Fig. 3.7 Paviken, Gotland, Sweden: possible mandrel with a bead added for museum display (Photograph: Matthew Delvaux).

3.3 Susteren-Salvatorplein, Limburg Province

Site: 4
Site type: Monastery
Province: Limburg
Municipality: Echt-Susteren
Place: Susteren
Toponym: Salvatorplein
Start date: 714
End date: 1802
Description: In the 1990s, excavations by the former Archaeological State Service (ROB) took place immediately north of the basilica of St Amelberga, the Romanesque church which is still standing today. These revealed remains of a monastery which was inhabited from the 8th century until it was dissolved in 1802 during the French occupation. The monastery was almost completely demolished in the early 19th century. The results have recently been published by Henk Stoepker.[181]

The foundation of the monastery and a small church is recorded in a charter from 714 when Pepin II and his wife Plectrude donated a small estate on the river Suestra to the Anglo-Saxon missionary Willibrord. The stream was part of a larger drainage system in the Limburg Meuse Valley. The excavations yielded only scant evidence for late Merovingian habitation, consisting of a timbered building with several associated waste pits and an oven, a cistern and a few graves. Very few portable finds were recovered from this period.

The period of the late 8th century and 9th century sees an increase in habitation and there were now two stone buildings, one of which was circular and may have been a funeral chapel, a timbered building, as well as the above-mentioned cistern; to the east of the buildings was a craft zone with a bell-casting pit

175 Heaser 2018.
176 Lundström 1981, 99–100, fig. 10:4. With many thanks to Matthew Delvaux, Princeton University, for providing the reference and translating the Swedish text into English.
177 Sode 2004, 86, fig. 3.
178 Information and photographs are kindly provided by Wim Dijkman, Senior Conservator Archeologie en Erfgoed, Team Programma en Innovatie, Centre Céramique – Kumulus – Natuurhistorisch Museum.
179 Isings 1957, 113–114.
180 Bead type B5.2-2a, Period 3; Bead type B1.2, Period 4 (Vrielynck, Mathis & Pion 2018).
181 Stoepker 2021.

and five ovens. This development is mirrored by an increase in the number of graves; these are presumably associated with the early medieval abbey church which is likely to be found beneath the present-day Romanesque church. Finds of highly coloured quarries are typical for ecclesiastical contexts and are a testament that stained glass windows were in use, most likely in the abbey church.

A watercourse (complex 4300/4400) north of the habitation zone was used as a refuse dump from which many Carolingian period finds were retrieved. As much as 85% of Carolingian pottery was imported from the German Rhineland, showing the monastery was firmly embedded in the Rhenish trade system, despite the location of the monastery on the Meuse. Wine glasses such as (palm-)funnels probably came from the same Rhenish production centres as the ceramics.

No indications were found for animal husbandry, although it can be assumed that nearby farms on (a) monastic estate(s) would have provided the monastery with animal products. The over-representation of certain skeletal elements of pigs shows these were specifically imported for the consumption of meat, one of the few signs of luxury enjoyed in the monastery.

During the first half of the 10th century, the habitation zone was cleared and a large amount of settlement refuse, including remains of buildings, was dumped in watercourse 4300, perhaps as a result of a Viking raid in 881–882, although no evidence was found to support this. For the period of *c.* 900 to *c.* 1050 only one wooden building, a well and graves are discernible, and possibly some ovens. There are significantly fewer portable finds than in the previous century. The building of a new, Romanesque church in the second half of the 11th century ushers in a new phase of the monastery, characterized by the construction of stone-built cloisters. The digging of watercourse 4200 in the 11th century, intersecting the early medieval watercourse 4300/4400 caused a lot of early medieval material to be redeposited in later contexts.

Glass production waste: Five fragments of glass production waste make it likely that glass was worked in the monastery, probably during the early medieval period.[182] The finds consist of two fragments of glass crucibles, a partially melted Roman tessera, a glass fragment from glassblowing tool and a possible fragment of opaque yellow raw glass. The crucible fragments derive from the same context in watercourse 4310 (800–1300 AD) which mostly contains redeposited Carolingian material (60%) and some 10th century (17%), 11th–12th century (22%) and Iron Age/Roman period (1%) material.

One crucible fragment is probably made of Carolingian Badorf ware[183] and presumably derives from the same type of cooking pot that was used at Utrecht-Domplein (Dorestad type W III) (see Section 3.5.1) and probably also at Leidsche Rijn (see Section 3.6.2). Unfortunately, the translucent light (bluish-)green natron glass is too contaminated to be linked to either the window or the vessel glass found at Susteren. The other crucible fragment of possible grey Meuse Valley ware is covered on the inside with a thin layer of translucent dark blue natron glass with a small area of colourless glass (fig. 3.8a).[184] The chemical composition of the dark blue glass in the crucible can be chemically linked to the dark blue glass of two translucent dark blue window quarries:[185] an irregularly shaped quarry from a grave dating to the late 10th/11th century and a small triangular quarry from a context in watercourse 4400 with predominantly high medieval material with some early medieval finds (8%).[186] High concentrations of antimony in all three glasses show that antimony-rich Roman tesserae were mixed in to colour the glass.

The find of a partially melted, opaque dark blue Roman tessera (fig. 3.8b) could suggest that dark blue glass for the production of window glass was made in the monastery by adding blue tesserae to a colourless base glass.[187] The tessera was found together with the above-mentioned triangular dark blue quarry and can be either high or early medieval. The number of artefacts involved is small but the presence of the crucible clearly shows that dark blue glass was being worked. The practice of recycling Roman tesserae, especially blue tesserae for colouring window glass, was carried on into the 12th century.[188]

A thick-walled fragment of translucent dark bluish-green glass is covered on the concave inside with dark grey iron scale from a glassblowing tool (fig. 3.8c). The fragment comes from the intersection of high medieval watercourse 4200 (11th–13th century) and early

182 Sablerolles 2023 (basispublicatie chapter 29).
183 Pottery identification by Jan de Koning.
184 Stoepker 2021, 229, afb. 11.11, V12-053-GL-10. Pottery identification by Jan de Koning.
185 Henderson 2023 (basispublicatie chapter 31).
186 Stoepker 2021, 231, table 11.1, V09-129-GL-01, V04-194-GL-01.
187 Stoepker 2021., 230, afb. 11.12.
188 Freestone 2015,.

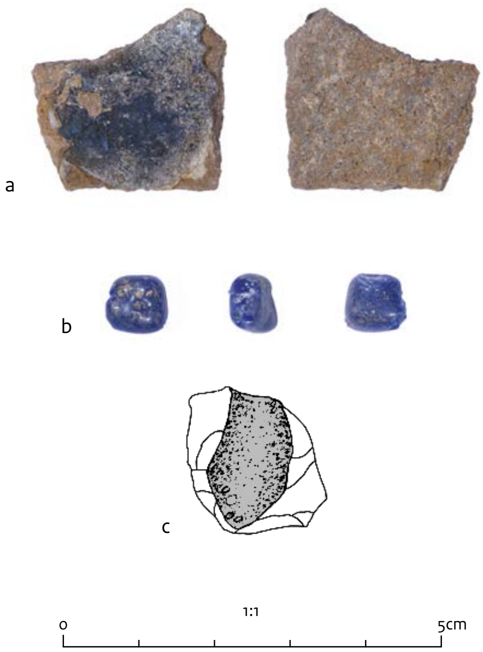


Fig. 3.8 Susteren-Abdijterrein: Glass-working production waste: a) fragment of a crucible with translucent dark blue glass on the inside (V12-053-GL-10); b) a partially melted, opaque dark blue tessera (V04-194-GL-02); c) a glass fragment from a gathering or bit iron (V12-078-GL-01) (Photographs: Limburgs Museum, Venlo. Drawing: SAGA Archeologie).

medieval watercourse 4300; the find context contains 25% early medieval pottery. It is possible that both crucible fragments and the glass fragment from the gathering iron were deposited closely together in watercourse 4310 and that the latter was redeposited when watercourse 4200 was dug.[189] The glass is well preserved and is likely to be natron glass rather than wood ash glass which makes an early medieval date more likely.

Whether early or high medieval in date, this fragment represents the only direct evidence for glassblowing in the Netherlands since the Roman period. The fragment is interpreted by the archaeologist and experimental glassblower Mark Taylor[190] as glass that was broken off a gathering iron or bit iron. A bit iron is a long, thin iron rod with a flat end which is used by glassblowers to add handles, feet or decorations to a glass vessel. Since no early or high medieval vessels with handles or added feet are known from the Netherlands, the fragment therefore most likely results from decorating a translucent bluish-green vessel with a self-coloured decoration such as a spiral trail. In the Carolingian period, self-coloured spiral trails were especially popular on the necks of globular jars. One bluish-green vessel fragment from Susteren may derive from such jars.

A fragment of opaque yellow glass from a 17^{th} century cesspit, which also contains some early medieval material, may be a raw glass fragment struck from an early medieval glass ingot. In northern France yellow glass was worked in several monasteries during the 8^{th} and early 9^{th} centuries to produce reticella wares, especially bowls decorated with yellow spirals and reticella rods.[191] A body fragment of such a bowl was also found at Susteren.[192]

3.4 Wijk bij Duurstede (Dorestad), Utrecht Province

An overview of glass-working waste from Dorestad was published by Preiß in 2010.[193] His inventory counts 84 finds which are made up of a few old finds without contexts as well as *in situ* finds from excavations in the late 1960s and ’70s in the harbour area (Hoogstraat excavations) and the settlement on the river bank (vicus). However, the majority of the finds (60%) were retrieved during more recent excavations in the agrarian settlement, the Parkeerplaats Albert Heijn (PPAH) excavations in 1992–1993 and the Veilingterrein excavations in 2007–2008, probably due to wet-sieving.

The largest category of glass waste is formed by tesserae (43%) which were recycled on a large scale in the early medieval period. They were melted down to make beads, especially in Scandinavia, or to increase the volume of glass batches intended for the production of window and vessel glass.[194] Preiß’s group of deformed glass (29%) may also include accidentally melted vessel fragments. The remainder is made up of glass drops and threads (15%), glass lumps (7%) and miscellaneous (6%).

A find worth mentioning in the last category is that of a crucible which was found before 1978; it comes from the vicus on the river bank and is now lost.[195] Isings described the fragment as follows: ‘Fragment of a crucible, pinkish grey ceramic. Covered by a layer of greyish green glass on the outside and a thick layer of green to bluish green glass on the inner surface.’[196]

[189] Stoepker 2021, 229.
[190] Many thanks to Mark Taylor of ‘Heart of England Glass’ (https://heartofenglandglass.co.uk) and ‘The Glassmakers’ (http://www.theglassmakers.co.uk).
[191] Louis 2015, fig. 4b, c, d; Cabart, Pactat & Gratuze 2017; Henton 2020.
[192] Stoepker 2021, 201, table 10.03, V08-190-GL-07.
[193] Preiß 2010.
[194] Henderson, Sode & Sablerolles 2019; Schibille & Freestone 2013, 2–3, fig. 1C, D.
[195] Isings 1978; Preiß 2010.
[196] Isings 2015, 444, No. 16035.

Perhaps the glass on the outside seems greyish green because the outside of the crucible had discoloured to a dark grey colour as the result of reheating, as can be seen on the crucible fragments from Utrecht-Domplein (see Section 3.5.1).

The glass production waste from the PPAH excavations and the Veilingterrein excavations is discussed in more detail below.

3.4.1 Wijk bij Duurstede – Parkeerplaats Albert Heijn (PPAH)

Site: 5
Site type: Settlement
Province: Utrecht
Municipality: Wijk bij Duurstede/Dorestad
Place: Wijk bij Duurstede
Toponym: Parkeerplaats Albert Heijn (PPAH) (Steenstraat/Zandweg)
Start date: 750–775
End date: *c.* 1250
Description: In 1992 excavations by the former Dutch National Service for Archaeological Heritage (ROB) were carried out at the intersection of Steenstraat and Zandweg before the construction of a car park for a planned new supermarket (Albert Heijn), hence the toponym Parkeerplaats Albert Heijn (PPAH).[197]

Fig. 3.9 Dorestad-Parkeerplaats Albert Heijn (PPAH) site: Glass working crucible with melted opaque white glass, probably from a Roman tessera. Defects in the transparent base may indicate where crushed tesserae were attached but have fallen out. Rim diameter 17.5 cm (Preiß 2010, 125, fig. 107). Not to scale.

Both Carolingian and later settlement traces were found. In the Carolingian period this area belonged to the settlement west of the vicus on the river bank. This settlement has a more agrarian nature as evidenced by farm buildings discovered later during the Veilingterrein excavations (2007–2008) further north along Zandweg (see Section 3.4.2). Carolingian features include ditches which seem to enclose (farm) yards on which posthole clusters, pits and wells were found. Most of the contents of the pits were sieved which yielded an enormous amount of glass fragments, including a rare gold-foil beaker, glass beads, bone artefacts and birds and fish bones. The bone artefacts included production waste. The adjoining Albert Heijn supermarket site also produced Carolingian period loom weights and traces of metal-working.[198]

Pottery finds were made up of the usual range of Carolingian wares, for instance Rhenish and Eifel ceramics, as well as younger wares from Pingsdorf, Andenne and Paffrath. The finds prove this part of the settlement remained inhabited after the Viking attacks and only shifted in a south-easterly direction in the mid-13th century, where the town of *'Wiic bi Duerstede'* would develop.

Glass production waste: Some thirty-six fragments of glass-working waste, including eight tesserae, were found distributed throughout this part of the settlement (trenches 810–815).[199] Among these was a large fragment of a glass crucible (fig. 3.9). It was found in a pit together with other glass-working waste made up of two blue tesserae, a regular and an irregular drop of translucent pale green glass, a small, dark sphere, six melted lumps of translucent pale green vessel glass and a melted fragment of 'black', deep olive-green glass. The crucible belongs to a pluriform group of bowls (type WX in the Dorestad typology)[200] which are late Merovingian in origin and are made in different production centres in the Rhineland. On the Dorestad-Veilingterrein site they are mostly 8th century in date and are also found in Carolingian yards.[201]

The inside of the crucible is covered with a thin layer of almost colourless glass of *c.* 1 mm thickness with a thicker patch of opaque white glass which probably represents (a fragment of) a melted tessera. Preiß points out that defects in

197 Van Dockum 1997.
198 Nyst 2003, 13.
199 Nyst 2003, 32, catalogue 4.2; Preiß 2010 passim.
200 Van Es & Verwers 1980.
201 De Koning 2012, 186.

the translucent glass probably indicate locations where other (crushed?) tesserae had been attached.[202] The crucible can be linked to bead-making, but also to vessel or window glass production.

3.4.2 Wijk bij Duurstede – Veilingterrein and Frankenweg/Zandweg

Site: 6
Site type: Settlement
Province: Utrecht
Municipality: Wijk bij Duurstede
Place: Wijk bij Duurstede
Toponym: Veilingterrein (Zandweg) & Frankenweg/Zandweg
Start date: *c.* 600–650
End date: 900
Description: Due to their proximity these two sites have been treated as one. The archaeological remains belong to the same agrarian settlement west of the vicus and harbour works as the PPAH-excavations (see Section 3.4.1).

The excavation Frankenweg/Zandweg was carried out by the Archeologisch Diensten Centrum (ADC) in 2001 before the planned construction of an apartment block on this site.[203] During the Merovingian phase (*c.* 600–725) no buildings were found, but four wells indicate there must have been some. It was only possible to reconstruct one Carolingian-period building with a boat-form, possibly a farmhouse. Other Carolingian features are ditches and eight wells. Metal slags were found as well as waste products from antler-working and possibly glass-working. Habitation decreased dramatically during the third phase (late 9th–10th century) and was discontinued during the high middle ages when the area was in use for arable farming.

Immediately south of the 2001 excavation, the ADC carried out another, much larger excavation (1.7 ha) on the site of a former fruit auction (Veilingterrein) along Zandweg.[204] The archaeological remains belong to the same agrarian settlement west of the vicus and harbour works as the PPAH excavations (see Section 3.4.1). Habitation started in the Merovingian period around 650. Three large farm yards were identified in this area. On these, the remains of two farmhouses were identified as well as twelve wells, many waste pits and inhumations. In the third quarter of the 8th century a new partition of the land took place into rather narrow strips of land, clearly delineated by ditches. These boasted eight buildings, 112 wells, many pits, latrines and oven-pits. Seven boat-shaped farmhouses were identified and one building with straight sides, its function is uncertain. The farm houses do not show obvious differences in size or layout.

Several yards yielded evidence for iron-smithing and weaving wool, one (yard K4) provided clear evidence for specialized crafts, namely amber-working and the production of brass (terminus post quem 800), while finds of two touchstones with traces of gold and the largest concentration of coins point to trade activities in this yard.

A large amount of pottery from the German Rhineland and the Eifel, mill stones from the Eifel, wine glasses most probably from the Rhineland, wine (in barrels) from the middle Rhine region, combs from Scandinavia, and Roman tesserae, possibly from the Mediterranean, underline the international character of the settlement and the importance of trade.
The period between 875 and *c.* 1050 saw a steep decline in habitation and only one farmhouse can be identified, while three were found dating between *c.* 1050 and 1300. From *c.* 1300 onwards, the area was used for arable farming.
Glass production waste: The glass production waste from the Veilingterrein was published in 2012 in a monograph on the excavations, and recently in an overview article on the beads from Dorestad.[205] Tesserae make up the largest category (n=13), almost all in the blue/green colour spectrum. Fragments of translucent bluish-green and dark blue glass point to imports of (chunks or ingots of) raw glass. One bluish-green flake was struck off from a larger lump of raw glass and has an imprint of a glassworker's tool (fig. 3.10). The small diameter of the tool makes it more likely it was a bead-working tool (punty).

Two convex fragments of dark blue glass (fig. 3.10) clearly belong to plano-convex 'cakes' also found on Scandinavian bead-making sites such as Åhus, Sweden.[206] There are three glass drops in corresponding colours (fig. 3.10). Two glass rods of opaque yellow glass (square-

[202] Preiß 2010.
[203] Sier, Van Doesburg & Verwers, 2004.
[204] Dijkstra, 2012.
[205] Sablerolles & Henderson 2012, 326–333; Langbroek 2021b.
[206] Callmer & Henderson 1991, fig. 2.

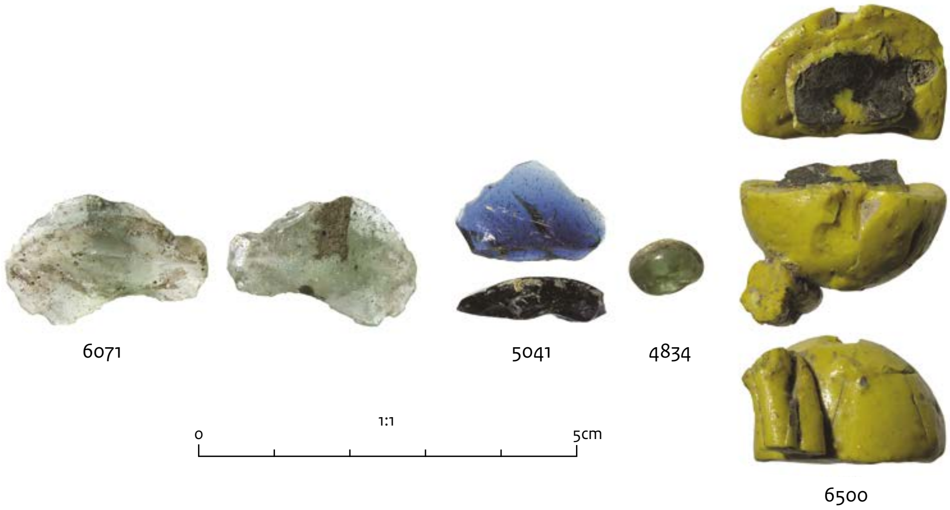


Fig. 3.10 Dorestad-Veilingterrein site: A translucent bluish green flake of raw glass with imprint from a probable punty (6071), a convex fragment from a translucent blue glass 'cake' (5041), a plano-convex drop of bluish green glass (4834), an opaque yellow glass lump with a section of an opaque yellow composite rod and a fragment of punty glass (6500) (Sablerolles & Henderson 2012, fig. 6.19).

sectioned) and white glass (round-sectioned) are likely to be associated with bead-making. A lump of opaque yellow glass has part of a composite opaque yellow glass rod and yellow punty glass from a glassworker's tool melted onto it (fig. 3.10). Composite glass rods were also found on the Merovingian bead-making site of Maastricht-Jodenstraat and can be linked to bead-making (see Section 3.2.1).

An opaque green object, first believed to perhaps represent the pinched end of a glass rod,[207] is actually a failed, wound bead and represents waste from glass bead production.[208] A fragment of a twisted bichrome rod has a translucent bluish-green core with an opaque white trail twisted round it. In the Carolingian period reticella rods with translucent greenish cores and opaque twisted trails were used to decorate vessel glass. Twisted bichrome cables have been found at the French monasteries of Hamage and St Amand-les-Eaux on the river Scarpe, where they were used to decorate globular jars and bowls.[209]

A thick, flat piece of opaque yellow glass shows black traces of iron oxide scale in the fractures on the sides as well as what seem to be small amounts of ceramic (from a crucible?) or red-baked clay.[210] This yellow glass could have been intended for bead-making or for decorating 8th century vessel glass, funnels, jars and bowls, with yellow trails. Finally, a quantity of melted bluish-green glass adheres to a fragment of red-baked clay.[211]

In several contexts on the above-mentioned yard K4, a small concentration of glass bead production waste, including four tesserae, was found together with waste from amber-working, raising the possibility that either a beadmaker was working here side by side with an amber-worker or that both crafts were carried out by the same craftsman. A combination of waste from amber and a small concentration of bead-working waste, including five tesserae, is also found on the northernmost yard (yard K1), which saw most activity around 800.

Finally, from the 2004 excavation (Frankenweg/Zandweg), a tessera of 'bright blue glass' and a lump of clay covered with a thick layer of 'blobby greenish glass' were found immediately north of yard K1 on the Veilingterrein site.[212] These are not included in Preiß's 2010 overview of glass production waste from Dorestad. Nor are two small spheres of whitish glass, possibly weathered translucent glass.[213]

These finds point to the local production of beads, but the production of vessel glass cannot be excluded.

There is a relatively small amount of glass production debris, but it is worth considering that, in contrast to the situation in the famous Danish bead-making site of Ribe, no original floor surfaces were preserved, so only finds from pits, wells and ditches were recovered, and that wet sieving was only carried out in specific

207 Sablerolles & Henderson 2012, 329–330, afb. 6.21, findnr. 5791; Langbroek 2021b, table 7, findnr. Veilingterrein 5791.
208 Langbroek 2021b, fig. 12.5, 64, table 7, findnr. Veilingterrein 5791.
209 Lassaunière *et al.* 2016; Henon 2020.
210 Langbroek 2021b, table 7, findnr. Veilingterrein 1195.
211 Sablerolles & Henderson 2012, 326–333, afb. 6.21, 5791; Langbroek 2021b.
212 Van Doesburg 2004.
213 Langbroek 2021b, table 7, findnrs Zandweg WD 754.2.63b, WD 754.2.63b.

instances.[214] It is therefore hard to gauge whether this constitutes small-scale production at household level, production for local demand or (supra-)regional production.

3.5 Utrecht, Utrecht Province

Utrecht may be one of those rare places in the Netherlands where there are indications for Merovingian glass-working – though we need to await the final results of the post-excavation work to establish if there is more comprehensive evidence – as well as evidence for glass-working in the Carolingian period.

3.5.1 Utrecht-Domplein

Site: 9
Site type: Proto-urban settlement
Province: Utrecht
Municipality: Utrecht
Place: Utrecht
Toponym: Domplein
Start date: *c.* 40
End date: present day
Description: The Domplein (Dom Square) in Utrecht city centre is named after the Domkerk (Dom church or St Martin's Cathedral) which dominates the central square. Excavations carried out in the 20th and 21st centuries have made clear that the square was continually inhabited from the Roman period to the present-day. Small-scale excavations took place between 1927 and 1949.[215] These revealed parts of an auxiliary fort – Traiectum – which was first constructed in the 40s of the 1st century. After four wooden phases, it was rebuilt in stone around 200 and abandoned during the course of the 3rd century. Furthermore, evidence for Carolingian and high medieval habitation was found, as well as remains of the 11th century imperial palace – Lofen.

Excavations in 1993 of part of the Heilig Kruiskapel (church of the Holy Cross), which was demolished in 1829, made clear that the church was probably founded around 700, rather than in the 10th century as was suggested in 1929. This has led to speculation that this simple hall church may be identified as one of two churches reputedly built here by the Anglo-Saxon missionary Willibrord around 695: either the now-lost church of St. Salvator (Sint-Salvatorkerk) or the church of St. Martin (Sint-Maartenskerk), the predecessor of the present-day Dom church.

Glass production waste: In total, 17 fragments of glass crucibles were found during excavations in 1933 at the site of the Roman castellum on or near the Domplein (table 3.5).[216] Of these, five were published in 1934 and illustrated by the famous Dutch artist and illustrator Anton Pieck (fig. 3.11).[217] Three of the published fragments (body fragments 203, 204 and B8) were not among the crucibles made available for sampling carried out at the Cultural Heritage Agency of the Netherlands (RCE).[218] Two of the latter were found just west of the Domplein in 'Flora's hof' (courtyard). Judging from the illustration (fig. 3.11), the glass colours in these

214 Dijkstra 2012, 25–27, 591.
215 Wynia 2013.
216 Vollgraff & Van Hoorn 1934, 63–64. The objects are part of the collection of the *Provinciaal Utrechts Genootschap van Kunsten en Wetenschappen* (PUG) or the Provincial Society for the Arts and Sciences (PUG findnumber 234).
217 Vollgraff & Van Hoorn 1934, pl. XXII.
218 The crucibles were sampled by Hans Huisman, Dutch National Heritage Agency (RCE), Amersfoort.

Fig. 3.11 Utrecht-Domplein site: Illustration of glass crucible fragments by Anton Pieck (Vollgraff & Van Hoorn 1934, 63-64, pl. XII); top row: findnrs 234 (rim), 203 (body); middle row: findnrs 204 (body), B8 (base); bottom row: findnr B8 (body) (Vollgraff & Van Hoorn 1934, pl. XXII).

crucible fragments are a deep blue-green rather than 'dark green' and pale bluish green rather than 'pale green'. Six photos of the glass production waste are given at Appendix IV (figures appendix IV.39-45).

At the time of the excavation, the fragments were erroneously believed to be Roman in date, but in a publication of 2009 a rim fragment (DPL-234) and a base fragment (DPL 1933-zn3) were published as fragments of (a) Carolingian globular pot(s).[219] Judging from photographs of the objects, all the other fragments probably also belong to this type of pot (see Dijkstra's contribution below). Based on the find locations, the glasses inside the pots and their fabrics, at least eight pots are represented, but this number may have to be adjusted in future when the fragments themselves are studied.

Two rim fragments have off-white deposits on the inside below the rim, on top of the rim and on the outside, just below the rim (DPL 1933 234, DPL 1933 zn2. The composition of these white deposits will be discussed in more detail in Chapter 5. A rim fragment (DPL 1933 234) has two very thick deposits of translucent glass which start just below the rim and are sticking out above it. This is likely to be the result of an attempt at removing the last remains of viscous glass from the crucible which solidified just before it could be poured out.

It was suggested by Isings *et al*. that glass production on the Domplein is linked to making red glass inlays for jewellery or beads.[220] A recent discovery of a glass bead workshop at Ribe dated to between 760 and 790 yielded fragments of a crucible with the remains of recycled Roman green glass with streaks of red and brownish coloration caused by iron and copper. It is suggested that this glass was used for the production of opaque red cylindrical beads and black wasp beads[221], bead types that were also found at Dorestad.[222]

The glass inside the crucibles at Utrecht Domplein may well represent an attempt at making opaque red glass. However, red marbled translucent blue-green/bluish-green glass was popular in the late Merovingian and Carolingian periods for the production of vessel glass, especially bowls and bulbous jars,[223] and for flat glass intended for stained glass windows. A fragment of a Carolingian red marbled blue-green glass quarry was found at the early medieval monastery at Susteren (Limburg Province) (fig. 3.12), where there are indications for the production of window glass, most likely in the Carolingian period (see Section 3.3).[224] In the context of the Domplein, production of window glass is certainly a possibility since there was at least one church here in the 8th century (see above). Interestingly, the monastery at Susteren had special links with the church of Utrecht as it had been founded by the Anglo-Saxon missionary Willibrord (see Section 3.3).

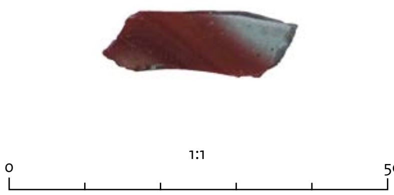


Fig. 3.12 Susteren-Abdijterrein: A fragment of quarry of translucent blue-green glass with red marbling (Stoepker 2012, table 11.1; Sablerolles 2023).

Glass crucibles: Utrecht-Domplein
Contribution by Menno Dijkstra (University of Amsterdam)

Based on the photographs, the crucible fragments probably all derive from Carolingian globular pots (Dorestad type W III)[225] dating between 750 and 875/900 (fig. 2.13). This is indicated by the three rim fragments as well as the relatively thin-walled body fragments and the lenticular base.

Fig. 3.13 Dorestad-Veilingterrein: Example of a complete Carolingian globular pot of Badorf ware (Dorestad type W IIIA) (De Koning 2012, afb. 4.28, findnr 503) (Photograph: Archeologisch Diensten Centrum (ADC). Height *c*. 17 cm.

219 Isings, Rauws, Lägers & De Kam, 2009, 48–49.
220 Isings, Rauws, Lägers & De Kam, 2009, 48–49.
221 Barfod, Feveile & Sindbæk 2022.
222 Sablerolles and Henderson 2012; Langbroek 2022.
223 See for instance Baumgartner & Krüger 1988, 71, No. 14, 72, No. 16.
224 Stoepker 2021, 230–232, Table 11.1; Sablerolles 2023.
225 Van Es & Verwers 1980, 81–87.

Table 3.5 Utrecht-Domplein: fragments of glass crucibles together with photo numbers and those scientifically analysed (Description of missing fragments from Vollgraff & Van Hoorn 1934, 63–64).

Find number (modern)	Find number (old)	N	Crucible	Glass	Sample	Sample number	Photo number
DPL 1933 zn2	?	1	rim	translucent bluish green & off-white deposit	DOM 5	35	figure appendix IV.43
DPL – zn3 (Flora's hof)	B8	1	base	translucent dark green glass (1 mm thick) marbled with opaque (purplish) red glass (0.5 mm thick)	DOM 3	33	figure appendix IV.41
Missing (Flora's hof)	B8	1	body	translucent pale green to dark green, red marbled	-	-	-
Missing	203	1	body	translucent dark green layer (1-6 mm thick)	-	-	-
Missing	204	1	body	translucent pale green glass, cracked (0.5–3 mm thick)	-	-	-
DPL 1933 234	234	1	rim	translucent bluish green marbled with opaque red	DOM 4	34	figure appendix IV.42
DPL 1933 73-84	?	4	rim	remains of translucent 'garnet' red glass in translucent bluish green glass	DOM 6	36	figure appendix IV.44
DPL 1933 77-53	B7	1	body	colourless glass (crucible: thin-walled beige fabric)	DOM 2	32	figure appendix IV.40
DPL 1933 77-56	B26	1	body	remains of opaque red glass	-	-	-
DPL 1933 77-36	B42	2	body	colourless glass	DOM 1	31	figure appendix IV.39
DPL 1933 77-57	B42	1	body	colourless glass	-	-	-
DPL 1933 77-31	B45	1	body	remains of opaque bright red glass	-	-	-
DPL 1933 77-58	B45	1	body	opaque bright red glass	-	-	-
Total		17					

Perhaps this type of globular pot was preferred because of its closed form. Crucible fragments of similar pots were probably found at the monastery of Susteren (see Section 3.3) and in Leidsche Rijn – Leeuwesteyn Noord (See Section 3.6.2).

The photographs show that the fragments are of a reddish colour on the inside and grey on the outside. One thin-walled fragment is beige on the inside (DPL 1933 77-53). The photographs show that the outside surfaces of the sherds are marked by small blisters which are located in places where the temper pierces the surface. These blisters are probably caused by reheating of the pots when reused as glass crucibles and may represent the early phases of vitrification.

The presence of rims and the fact that the base fragment and the body fragments are not covered by spilt glass on the fractures, indicate only complete pots were used. This is in contrast to the late 6th-century Maastricht-Jodenstraat (see Section 3.2.1) and early 7th-century Rijnsburg-Abdijterrein sites (see Section 3.8) where complete pots contained colourless or translucent blue-green glass, while only the lower parts of the pots were used for working relatively small amounts of highly coloured opaque yellow glass: by removing the upper parts of the pots, the beadmakers created wide-open 'bowls' that allowed for easy access to the glass.[226]

It is difficult to make a statement about the types of fabrics represented on the basis just of photographs (table 3.5). Moreover, it can be hard to distinguish the different types of tempers in rather thin-walled Rhenish fabrics from Badorf and Walberberg in the Vorgebirge and Mayen in the Eifel. Parts of the photographs of the cross-sections show the presence of quartz sand, but this can be present in both Mayen and Vorgebirge wares. Seven sherds show black specks, which are mostly tiny cavities, but some of them could be fragments of augite or hornblende, which are typical for Mayen fabrics (see table 3.6).

Other typical Mayen volcanic temper-like pumice grains and off-white specks (clay pellets) are almost absent, but this is not uncommon in thin-walled fragments. This thinness could also explain the absence of small red particles, probably ferronic nodules, which are sometimes noted in Vorgebirge fabrics.[227] Only the fabric of the sectioned rim fragment DPL 77-234 can with

226 Sablerolles, Henderson & Dijkman 1997, 304; Dijkstra, Sablerolles & Henderson 2011, 185–186.

227 Fabric details are based on Redknap 1988, 5 and 11; Bardet 1995, 221–230; Keller 2012, 213.

Table 3.6 Utrecht-Domplein: Rim type and fabric of the Carolingian globular pots used as glass crucibles.

Find number	Crucible	Rim type	Fabric (based on photographs)
DPL 1933 zn2	rim	W IIIA	coarse quartz sand, Walberberg fabric (Dorestad w-4?)
DPL 1933 234	rim	W IIIA	black specks etc., Mayen fabric (Dorestad w-12)
DPL 1933 73-84	rim	W IIIA	coarse quartz sand, Walberberg fabric (Dorestad w-8)
DPL 1933 zn3	base	-	black specks, Mayen ware?
DPL 1933 77-31	body	-	black specks, Mayen ware?
DPL 1933 77-36	body	-	black specks, probably Mayen ware
DPL 1933 77-53	body	-	not determinable
DPL 1933 77-56	body	-	Mayen or Walberberg fabric?
DPL 1933 77-57	body	-	black specks, probably Mayen ware
DPL 1933 77-58	body	-	black specks, Mayen ware?

W IIIA = globular pot of Badorf ware, dating between 750 and 875/900 (Dorestad type W IIIA).

confidence be identified as typical for the production centre at Mayen (Dorestad fabric w-12). Rim fragment DPL 73-84 can be identified as a Walberberg fabric (Dorestad fabric w-8) due to the temper with coarse quartz sand.

3.5.2 Utrecht–Oudwijkerdwarsstraat

Site: 10
Site type: Proto-urban settlement
Province: Utrecht
Municipality: Utrecht
Place: Utrecht
Toponym: Oudwijkerdwarsstraat
Start date: *c.* 600 (?)
End date: *c.* 750
Description: During building activities in Oudwijkerdwarsstraat just east of Utrecht old city centre, archaeologists of the municipality of Utrecht recovered remains of an early medieval settlement.[228] It comprises part of a large settlement that stretched along the former bank of the Kromme Rijn for at least 150 metres. An initial assessment of the pottery points to habitation in the 7th and first half of the 8th centuries. This find is very important for two reasons: not much is known about early medieval life in this part of Utrecht, and the finds are extraordinarily well preserved.

No house plans were found, since only the rear parts of farm yards were found. However, there are remains (postholes, clay) of probable subsidiary buildings, while ditches may represent yard boundaries. Waste pits yielded pottery, animal bones, millstones and loom weights, offering an insight into the economy of the settlement. About 1400 amber fragments, ranging in size from splinters to fairly large lumps, and including half-products, show amber was worked in the settlement. Never before has so much amber been found in Utrecht. The amber finds were concentrated in two shallow pits which yielded many other finds including 13 glass fragments. Furthermore, silver and copper coins and glass beads were also found.
Glass production waste: Glass production waste is scanty. An irregular drop/melted lump of translucent bluish-green glass (with a yellowish tinge) (WP 5-1-135) could be the result of glass-working, but could also be accidentally melted vessel glass. However, when vessel glass is accidentally melted, for instance in a hearth, it is usually possible to tell it is a deformed vessel fragment. The glass drop comes from a pit (S135) which yielded animal bones, pottery and burnt clay. This pit was only discovered when sectioning an adjacent pit (S62) which yielded pottery, metal, burnt clay, animal bones and three amber fragments. The pits are at a distance of 30 metres from the two shallow pits mentioned above with concentrations of amber. A small amount of glass (WP 6-1-170) seems to be crushed, perhaps in preparation for being melted down. Two photos of the glass production waste -OUDWIJ 1 (sample 78) and OUDWIJ 2 (sample 79)- are given at Appendix IV (figures appendix IV.45 and 46).

[228] Post-excavation is ongoing at the time of writing. Many thanks to Marieke Arkema, external archaeologist, Municipality of Utrecht, Ontwikkelingorganisatie Ruimte, Duurzame Stad, Erfgoed, for all initial information on the site.

3.6 Leidsche Rijn, Utrecht Province

The large early medieval settlement excavated at Leidsche Rijn has yielded sparse evidence for glass-working in the late Merovingian and Carolingian periods.

3.6.1 Leidsche Rijn-LR 51/54

Site: 11
Site type: Riverine settlement
Province: Utrecht
Municipality: Utrecht
Place: Utrecht
Toponym: Leidsche Rijn 51/54
Start date: 575
End date: 775
Description: In the period 2000–2001 a field survey, coring and a trial excavation were conducted as a result of plans to expand the A_2 highway in Leidsche Rijn located in the western part of the city of Utrecht.[229]
The archaeological research demonstrated that an early medieval settlement was situated here.

In 2005 a part of this settlement was excavated by the municipality of Utrecht (project LR51 and LR54). The excavations revealed that the early medieval settlement was located on relatively high land along the northern bank of the Oude Rijn. The second half of the 7^{th} and the early 8^{th} century formed the heyday of the settlement. In the course of the second half of the 8^{th} century habitation declined. However, a few stray finds from the 9^{th} century suggest that the area was also inhabited later, in the Carolingian period.
In total 88 early medieval buildings were found, which comprised 14 farmhouses and 74 outbuildings. Noteworthy are 34 large outbuildings with very long, pointed wooden posts, maybe granaries.

As only pollen (no grains) of oats, rye and wheat were found, the arable fields were probably not very close to the settlement. Farm animals were reared, especially cows and sheep. The lack of bones of 2-to-4-year-old cattle in the oldest and youngest habitation phases may point to the export of cattle during these periods. The diet was supplemented with riverine and imported marine fish as well as game. The inhabitants were engaged in (occasional) shipping activities and artisan production: iron was produced from imported iron ores and was also worked in the settlement; bronze and lead were worked.

Combs were produced from antler and seven fragments of raw amber point to amber-working. As much as 80% of the pottery was wheel-thrown, imported from the Rhineland together with the remains of at least seven late Merovingian drinking glasses (palm-funnels). Trade activities may have taken place, judging by the discovery of 37 early medieval coins. It is suggested that imported wares such as pottery, glass, millstones, iron ore, coal and amber could have been obtained with agricultural surplus stored in the granaries, as well as animal products.
Glass production waste: An opaque blue tessera was found in a waste pit on yard 3 in the eastern part of the settlement.[230] This yard also yielded most evidence for craft production: metal-working (iron and bronze), bone- and antler-working and amber-working. Moreover, almost all of the twelve glass beads were found on this yard, one of them in the same pit as the blue tessera, as well as most fragments of old, Roman and Migration period glass, which might represent cullet intended for recycling.[231] The pit is dated to the late Merovingian period which would make the tessera the earliest specimen in the Netherlands together with a tessera from Oegstgeest – Nieuw Rhijngeest Zuid (Rijnfront) (see Section 3.7).

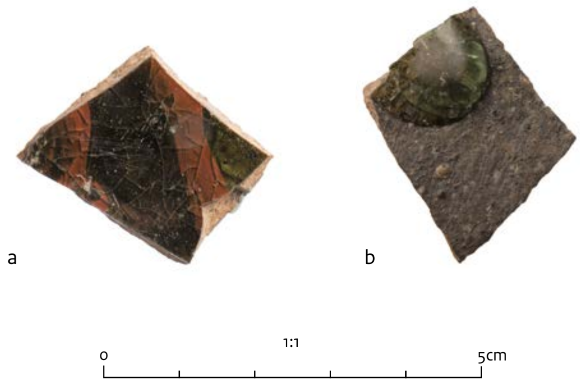


Fig. 3.14 Leidsche Rijn - Leeuwesteyn Noord: A fragment of a glass crucible, probably from a Carolingian globular pot (Dorestad type W III), a) covered on the inside with red marbled translucent greenish glass (left) and b) on the outside with a blob of translucent greenish glass (right) (Sablerolles 2019, fig. 7.15).

229 Nokkert, Aarts & Wynia, 2009.
230 Isings 2009, 247, afb. 11.2, table 11.1.
231 Isings 2009, 249, afb. 11, table 11.2, 250–251.

Although there is no glass bead production waste to accompany the blue tessera, the fact that it was found together with raw amber may point to a glassworker and amber-worker being active in this part of the settlement.

3.6.2 Leidsche Rijn-Leeuwesteyn Noord

Site: 12
Site type: Riverine settlement
Province: Utrecht
Municipality: Utrecht
Place: Utrecht
Toponym: Leeuwesteyn Noord
Start date: 575
End date: 850
Description: In 2015 and 2016 excavations, commissioned by the municipality of Utrecht and carried out by RAAP, took place immediately east of the early medieval settlement Utrecht-Leidsche Rijn LR 51/54 which was excavated a decade earlier (see Section 3.6.1).[232] The settlement, on the northern bank of the Old Rhine, was probably located in an outer, not an inner bend of the river as had previously been assumed.

The combined excavations have unearthed 275 metres of a large settlement which continues in easterly and westerly directions. The excavations confirm the idea proposed by the 2005 excavators that the settlement continued into the 9th century, probably till around 860.

Just as in Dorestad-Veilingterrein, the area was reorganized in the Carolingian period and (parts of) yards are delineated by north/south oriented ditches and picket fences.

Remains of two farms and several subsidiary buildings were found. This brings the total of houses in the Leidsche Rijn settlement to 14, while a total of 57 large subsidiary buildings were found. Of the latter, 37 are large, two-aisled buildings constructed with very long posts, deeply driven into the ground. They are interpreted as warehouses. It has been pointed out that similar structures are also found in some other 7th–8th century settlements along the Old Rhine (see Section 3.7) and it has been suggested that these could point to the existence of specialized settlements.

It was argued that the paucity of cereal grains in botanical samples collected during the 2005 excavations may indicate that (this part of) the settlement was geared towards craft and trade rather than agriculture. There is evidence for antler-working; metal-working evidence consists of iron-smithing and bronze-working. There is possible evidence for lime-burning. A glass crucible indicates glass was worked in the settlement.
Glass production waste: A body fragment of a crucible was recovered from one of the uppermost layers of the fill of the Old Rhine which contained both Merovingian and Carolingian pottery (fig. 3.14).[233] The fragment is reddish on the fracture, and grey on the outside, and is probably of a Carolingian globular pot (Dorestad type W III, fabric 12), similar to the crucibles from Utrecht-Domplein (see Section 3.5.1). The crucible is covered on the inside with a thin layer (1–1.5 mm) of translucent (bluish-) green glass marbled with opaque red glass, comparable to some of the Utrecht-Domplein specimens. A drop of translucent greenish glass was spilt on the outside.

In this context, it is less likely that this glass was being worked for the production of window glass as was suggested for Utrecht-Domplein. Perhaps, therefore, this glass was used for the production of beads. The only bead recovered from the site is a spiral bead from a Carolingian pit, made of faintly translucent greenish glass full of small bubbles, dark inclusions (iron fragments from a beadmaker's tool) and what looks like black/dark red streaks.[234] This bead may be one of the local products. It is similar to a bead found on the Maastricht-Rijksarchief site where beads were made (see Section 3.2.3).

3.7 Oegstgeest–Nieuw Rhijngeest Zuid (Rijnfront), Zuid-Holland Province

Site: 13
Type: Riverine settlement
Province: Zuid-Holland
Municipality: Oegstgeest
Place: Oegstgeest
Toponym: Nieuw Rhijngeest Zuid (Rijnfront)
Start date: *c.* 550
End date: 725
Description: From 2009 until 2014 the University of Leiden excavated a settlement dating to Merovingian times. Smaller parts of the settlement had already been excavated by

232 Norde 2019.
233 Sablerolles 2019, 136–138.
234 Norde 2019, 274–275, fig. 14.1, 7.

ARCHOL and ADC.[235] The Oegstgeest settlement has been excavated almost completely. It was of a modest size, with *c.* five or six contemporary farmsteads during its existence. Its population will not have been larger than *c.* 60 persons. It was located along the northern bank of the Old Rhine close to its estuary, some five km from the coast. The settlement was set in a landscape that was subjected to both riverine and maritime influences and was intersected by river arms, gullies and creeks, creating four quarters or 'islands' interconnected by one bridge and several small dams. Structures connected to shipping are jetties, quay works, and land abutments. As is the case at Rijnsburg-Abdijterrein (see Section 3.8) and Valkenburg-De Woerd (see Section 3.9), the farmhouses were laid out on a grid at right angles to a main gulley of the Oude Rijn. Each yard, enclosed by fences made of wattle, consisted of a farmhouse with several associated outhouses, multiple pits and wells. The postholes of the outhouses were remarkably deep and it is suggested that the buildings may have had raised floors enabling safer storage of agricultural produce.

Animal husbandry in the floodplains (cattle), some agriculture on the river levees, and fishing were the backbone of the economy. They also practised crafts such as smithing, and above all casting of copper alloy objects. Small and unexpectedly large crucibles show that this must have taken place to satisfy the needs of themselves and those in other settlements. Antler combs were made and amber-working was a widespread activity in the settlement. There is some tentative evidence for glass-working. Imported pottery from the German Rhineland, grain from löss areas, probably the Main area, wine (barrels) from the middle Rhine area and some exotic imports testify that this settlement made good use of its advantageous location along one of the most important early medieval supra-regional waterways, with the possibility to engage in exchange with the wider, early medieval world.

Glass production waste: Five fragments of possible glass production waste were found in five different locations: two fragments of tesserae, a possible fragment of a glass rod, a black drop and a trapezium-shaped fragment of translucent blue-glass with rounded edges.[236] Two weakly transparent green-blue fragments from a pit and a well from probable Roman tesserae could be the earliest evidence from the Netherlands for the reuse of tesserae by early medieval beadmakers, together with a specimen from the Merovingian settlement of Leidsche Rijn L51/54 (see Section 3.6.1). A colourless fragment is interpreted as part of glass rod used for winding beads. Since wound colourless glass beads were not common in the 7th century, it could perhaps also be a fragment of a reused Roman glass stirring rod. A drop of brown, almost black glass was split when it was heated. Small, spherical black drops have been found in association with glass bead production waste in Åhus, Dorestad, Maastricht-Rijksarchief and Wierum.[237]

The wound, monochrome and trailed beads found in the settlement (n=28) mostly date to the 7th century and show many similarities with half-products and wasters of beads found in the contemporary nearby bead production site at Rijnsburg-Abdijterrein (see Section 3.8).[238] The shapes, colours and decorations used are strikingly similar, including small flattened globular beads of opaque yellow, red and white glass, white beads with translucent bright blue crossing trails and a red bead with white crossing trails, and it is suggested that these beads could have been made in Rijnsburg-Abdijterrein.[239] Alternatively, they could have been made by travelling beadmakers who visited riverine settlements along the Old Rhine, including Rijnsburg-Abdijterrein and possibly Valkenburg-De Woerd.

3.8 Rijnsburg-Abdijterrein, Zuid-Holland Province

Site: 14
Site type: Riverine settlement
Province: Zuid Holland
Municipality: Katwijk
Place: Rijnsburg
Toponym: Abdij
Start date: 600
End date: 12th century

Description: Between 1944 and 1966 a series of excavations by the archaeological institutes of the universities of Groningen and Amsterdam and the former National Service for Archaeological Heritage (ROB, now RCE) took place on the site of a former Benedictine abbey

235 Hemminga & Hamburg 2006; Hemminga *et al.* 2008; Dijkstra 2011, 134; De Bruin 2018, 20–25; De Bruin, Bakels & Theuws 2021.
236 Langbroek 2021a, table 12.2, fig. 12.6.
237 Callmer & Henderson 1991, Table 1C, 1; Preiß 2010, number 47; Henderson, Sode & Sablerolles 2020, 78.
238 Langbroek 2021a, fig. 12.2.
239 Langbroek 2021a.

(*c.* 1130–1574), immediately east and north of the present-day church.[240] The excavations of this convent led to the discovery of various older settlements lying underneath. The oldest phase of the settlement dates to around 600 AD, when the southern bank of the Vliet was divided with wattle fences into small north-south oriented plots where several rectangular longhouses and secondary buildings were built, that can be associated with three or four generations of occupation lasting until around 720. It was situated in a tidal saltmarsh at the southern bank of a creek (the Vliet) of the Oude Rijn, close to the former mouth of the river. The economy was primarily based on farming, although traces of oven-/furnace-like structures, possible outdoor hearths, smithing slags and a few *tuyères* point to iron-working, while two crucibles, bronze fragments and a probable casting mould point to bronze casting. One of the smaller buildings close to the creek is believed to be a possible home of a smith and his family. A few lumps of amber may point to amber-working. The evidence for the production of Merovingian type beads also comes from this phase of the settlement. During the late 6th century and the early decades of the 7th, the settlement can be considered part of a probable central place complex located in the mouth of the Rhine.[241] Therefore, it could have been at the invitation of a local or regional ruler that a Merovingian beadmaker travelled to the settlement to produce fashionable glass beads.

In the second phase (720-890) a new type of boat-shaped house appears; apart from its shape, there was a difference in orientation pointing to a different organisation of the plots. It is not clear whether there was a short hiatus in habitation. In the Carolingian period a chapel and a cemetery were added.

Settlement traces which can be identified with the fortress of *Rinasburg* date between 890-1050 (phase 3), followed by the building of a new church accompanied by a farm or possibly a rectory (1050-1130, phase 4) and a Benedictine nunnery in the 12th century (phase 5).

Glass production waste: Virtually all waste from glass bead production debris was found in a feature which mainly consisted of fired clay, the remains of a hearth or possibly a rudimentary glass furnace. There may be a connection with one of the small buildings in the immediate surroundings, a possible home of a smith and his family. Glass bead production took place during the second generation (phase 1b, *c.* 610–640) or third generation of building (phase 1c, *c.* 640–680).

The glass bead production waste (objects) consists of finished, unfinished and failed beads (n=68), glass rods (n=45), punty glass from a beadmaker's tool (n=3), crucibles (n=8) and one undiagnosed fragment. Two lumps of fired clay covered with translucent greenish glass may be from the furnace floor.

Several categories represented among the bead production waste from Maastricht-Jodenstraat (see Section 3.2.1), such as glass drops and pulled threads, are missing at Rijnsburg. Scrap glass is also lacking. The latter is perhaps a coincidence, but it was noted that not a single fragment of Merovingian glass vessel was found in the entire settlement or in the nearby cemetery.

Excluding the crucibles, the waste categories are dominated by opaque yellow glass (an average of 49.6%), followed by opaque white (24.8%), opaque red (18.8%), opaque turquoise (5.1%) and opaque orange (1.7%).

Beads that were produced in the settlement include monochrome globular, bi- and tri-globular beads of opaque yellow glass, and bi-globular beads of red glass. Trailed beads include bi-globular beads of red glass with both white crossing trails and a white spiral, tri-globular beads of opaque red glass with opaque white crossing trails and white beads with translucent blue crossing trails.

In the context of the beads from the cemetery of Schretzheim, Koch was quoted as stating that beads with narrow crossing trails represent *billige Massenware* and are ubiquitous in necklaces of the later 6th and 7th centuries.[242] This date can now be refined by a more recent bead typology developed for beads from cemeteries in Belgium by Pion and Vrielynck, Mathis and Pion. [243] The above-mentioned bead types are all typical for Pion's Bead period 4 (600–640) (Table 3.7). Given the types of beads that were produced here, it is therefore most likely that the rudimentary furnace was in use during settlement phase 1b (*c.* 610-640).

Most of the beads were split during manufacture, either due to overheating of the glass or not annealing the beads properly after manufacture, a common occurrence on bead-making sites (see Section 3.2.1 and Section 3.12).

240 Dijkstra, Sablerolles & Henderson 2011; Dijkstra 2011, 114-133.
241 Nicolay 2017.
242 Koch 1977, 207, Farbtaf. 3, Gruppe 34.
243 Pion 2014; Vrielynck, Mathis & Pion 2018.

Table 3.7 Rijnsburg-Abdijterrein: A selection of locally produced beads, their typology and bead periods (Pion 2014; Vrielynck, Mathis & Pion 2018).

Form	Colour	Decoration	Type	Period
Bi-globular	opaque yellow	-	B1.2-1b	P4
Tri-globular	opaque yellow	-	B1.2-1c	P4
Bi-globular	opaque red	-	B1.2-2b	P4
Bi-globular	opaque red	white crossing trails & 1 white spiral	B5.2-1h	P4
Tri-globular	opaque red	white crossing trails	B3.2-1c	P4
Globular	opaque white	translucent blue crossing trails	B3.3-3a	P4

Period: P4=610-640 AD.

Chemical analysis of the glass from Rijnsburg-Abdijterrein indicates that the rods are of a very similar composition to the beads and therefore that the beads are very likely to have been made from the rods on site. Furthermore, the opaque yellow glass from the crucible fragments – although not associated with the production waste from the furnace – is proven to be of the same general chemical lead-stannate composition as the opaque yellow glass production waste.

Five fragments of glass-bearing crucibles were retrieved from different contexts within the Merovingian settlement, although one may derive from a section through the furnace. During the campaign of 1963 three fragments of crucibles were found, of which two smaller fragments derive from contexts which had intrusions from later periods. There are six base fragments and two body fragments. These belong to coarse-ware cooking pots (*Wölbwandtöpfe*) which were deliberately broken to obtain their bases for use as shallow, dish-like crucibles, comparable to those from the Maastricht-Jodenstraat site (see Section 3.2.1).

When initially investigated, the crucibles were thought to have glass attached to them. However, no detailed scientific analysis was carried out as part of this project to ascertain whether this material is glass or not. A base covered with what appears to be yellow glass on the inside and on the fracture may come from a section through the 'furnace'. A body fragment has what appears to be opaque yellow glass over a white layer, together with a greenish spot with streaked colourless and yellowish glass-like material lying over it; the streaked material covers the fracture while opaque yellow and yellowish/white spots can be seen on the outside. A small base fragment has opaque yellow material sticking to the outside of the base and colourless glass with small opaque yellow spots on the inside; a second small base has the same characteristics. A body fragment has a thin layer of colourless glass on the inside and an irregular, bubbly glass layer on the outside, indicating this was probably overheated and bubbled over. None of the fragments show any traces of vitrification. The remaining three bases show traces of vitrification on the outside and may have been used for glass- or metal-working.

It was suggested that a colourless base glass was modified on site using lead-tin-yellow pigment. Further scientific research needs to be carried out in order to investigate/ confirm whether fully formed yellow glass is present.

3.9 Valkenburg-De Woerd, Zuid-Holland Province

Site: 15
Site type: Riverine settlement
Province: Zuid-Holland
Municipality: Katwijk
Place: Valkenburg
Toponym: De Woerd
Start date: 525
End date: 950
Description: Excavations between 1986 and 1988 by the former National Service for Archaeological Heritage (ROB, now RCE) revealed the remains of an early medieval settlement at Valkenburg-De Woerd. The provisional findings were published in 1987 and 1990.[244] The settlement was laid out

244 Bult & Hallewas 1987; Bult, Van Doesburg & Hallewas 1990.

on a natural levee along the inner curve of a meander of the Oude Rijn, between gulleys on either side. The settlement was just a few kilometers away from the early medieval settlement at Oegstgeest-Nieuw Rhijngeest Zuid (Rijnfront) on the opposite side of the river.

The history of Valkenburg-De Woerd begins at the establishment of the Roman *limes*. In the mid-first century CE a military entrepôt harbour was laid out here, which must have been part of the *vicus* of *castellum* Valkenburg. Roman occupation ceased around 230 AD. Ceramic finds from a transect cut across a gulley of the Oude Rijn date between 525 and 950, with most finds dating to the 8th–9th centuries.[245]

The shore was divided into plots laid out on a grid at right angles to the river, similar to the situation at Oegstgeest-Nieuw Rhijngeest Zuid (Rijnfront) (see Section 3.7) and Rijnsburg-Abdijterrein (see Section 3.8). There were probably six to eight yards (width *c.* 50 m) divided by ditches, simultaneously at any given time during the Merovingian and Carolingian periods. The plans of the buildings are very unusual, mostly two-aisled, and are difficult to interpret. Farms like those found at Rijnsburg-Abdijterrein and Oegstgeest Nieuw Rhijngeest Zuid (Rijnfront) are lacking. Dijkstra points out that in the Merovingian period, two-aisled buildings functioned as barns and he hypothesises that the buildings on De Woerd may have combined two functions: traders may have lived and worked in them, while the buildings were used to store products or agricultural produce during the trading high-season, drawing a comparison with two- and three-aisled buildings on the dams in the Dorestad harbour.[246]

In the south-eastern part of the settlement the remains of revetments and a jetty were found, underlining the importance of the river as a mode of transport. There is evidence of bone- and antler-working and of livestock rearing.

Glass production waste: A glass crucible fragment (Find No. 510-4-307) was found in one of the trenches (trench 510) cut across the river. The crucible is covered on the inside with a thin, even layer of translucent pale greenish glass. A recent examination of the crucible by Epko Bult, University of Leiden, revealed it is a lower body fragment of a Merovingian *Wölbwandtopf* dating to the 7th rather than the 6th century. The crucible may, therefore, be contemporary with the crucibles from the nearby settlement at Rijnsburg-Abdijterrein and could be linked to bead-making (see Section 3.8).

3.10 Den Haag-Frankenslag, Zuid-Holland Province

Site: 16
Site type: Coastal settlement
Province: Zuid-Holland
Municipality: Den Haag
Place: Den Haag
Toponym: Frankenslag (Johan van Oldenbarneveltlaan 91–95)
Start date: 500–550
End date: around 700

Description: Small-scale excavations (385 m^2) carried out by the municipality of Den Haag in 1984 yielded part of a Merovingian settlement located on the eastern side of a coastal barrier.[247] The settlement started in the first half of the 6th century and ended in the late 7th or early 8th century. Shortly afterwards, there is evidence for arable farming until the settlement was covered by drift sands (the Younger Dune formation phase-0). The remains of pits, hearths, three houses, and two successive sunken huts were found which were probably used for weaving.

The inhabitants grew rye and barley on the nutrient-poor sandy soils, and reared cattle and sheep. They supplemented their diet with locally caught marine and riverine fish, game and wild fruit. Locally sourced bog iron was processed for the production of iron. Finds of Rhenish pottery and millstones, bronze and lead are believed to have been obtained by generating agricultural surplus. The Meuse and Rhine river systems could have been accessed over land (by way of the coastal barriers or the beach) or by sea.

Glass production waste(?): A few sherds of brittle hand-made pottery were found in a sunken hut. They are covered on the inside and outside with dark, deep blue-green 'glass', perhaps due to vitrification of the fabric of the crucible.[248] It is not clear if these fragments represent waste from glass- or metal-working.

[245] Jezeer & Jongma 2002 (in Dijkstra 2011).
[246] Dijkstra 2011, 172.
[247] Magendans & Waasdorp 1989.
[248] Magendans & Waasdorp 1989, 33; see also Dijkstra, Sablerolles & Henderson 2011, 192.

3.11 Bloemendaal-Groot-Olmen, Noord-Holland Province

Site: 17
Site type: Coastal settlement
Province: Noord-Holland
Municipality: Bloemendaal
Place: Bloemendaal
Toponym: Groot Olmen
Start date: 675
End date: 850
Description: In the dunes of the National Park Zuid-Kennemerland near Bloemendaal early medieval remains were found at 14 different locations.[249] The remains, which had been buried under the Younger Dunes (formed between 1200 and 1600), appeared when the area was restored to its former 'driftsand' state by de-turfing. In 2006 and 2007 Hollandia excavated a settlement (location 1-3) dating between the 5th and 7th centuries. A survey combined with some small trial trenches carried out by the ROB prior to the Hollandia excavations showed that locations 4, 5, 8 and 14 were in use during the 8th and early 9th century. Hollandia excavated locations 8 and 14 which were part of the same settlement.

In total, seven buildings were discovered, one barrel-lined well and remnants of fences. Site 8, where habitation layers were partially preserved, represented a single building dated to the 9th century. Site 14 yielded the remains of six buildings, including three house plans with a distinct boat-shaped form comparable to 'urban farms' found in Dorestad-De Heul. This imported building tradition most probably originated in the central riverine area and the Veluwe.

Evidence points to the agrarian nature of the settlements, while marine fish and molluscs played a more important role in the diet than in the older settlement (location 1-3). Pottery, glass, millstones and whetstones were imported from the Rhineland and the Eifel. In the 8th century the North-Holland coastal region was incorporated into the Carolingian empire and it has been suggested by de Koning that the settlement at Bloemendaal-Groot Olmen may have been connected to a royal domain which, according to historical sources, was located in the area around nearby Velsen.[250]

Glass production waste: A surface find of an opaque dark blue tessera was found near location 14 (8th–9th century).[251] This location also yielded a few fragments of thick-walled, blue-green Roman glass which could be cullet intended for recycling, perhaps to make the kind of globular 'bottle' blue-green bead that was also recovered from this location.[252]

3.12 Wijnaldum-Tjitsma, Friesland Province

Site: 18
Site type: Terp settlement
Province: Friesland
Municipality: Harlingen
Place: Wijnaldum
Toponym: Tjitsma
Start date: *c.* 50 AD
End date: 950–12th century?
Description: In 1990 fragments of a 7th century gold cloisonné royal brooch were found in a field on the Tjitsma terp near present-day Wijnaldum by metal detecting. Its footplate had already been found by chance in the 1950s. These finds were the catalyst for the excavations that were carried out by the Universities of Groningen and Amsterdam on the eastern crest of the terp settlement between 1991 and 1993.[253] Although they yielded a wealth of information, no tangible remains of the king or a royal residence were found. A second volume on the ceramic assemblage was published in 2014.[254]

The early medieval artificial mound or terp settlement at Wijnaldum was located on a salt marsh ridge which was oriented east-west. There is evidence it was settled since the 1st century AD. It was one of a number of closely spaced terps by the salt marsh which was open to the sea. It is assumed that it was quite densely populated since the Roman period, including during the early middle ages.

A recent field survey has shown that the beginning of habitation probably started as early as the 1st century.[255] The end of habitation on the terp may have come in the 12th century when the last farmstead may have moved to a separate house terp, just like other farms in the terp region.

The heyday of the terp settlement was the period between 550 and 650 when the area

249 De Koning 2015.
250 De Koning 2015.
251 De Koning 2015, 317–318, afb. 11.6.
252 Sablerolles & De Koning 2015, 311–316, afb. 11.1, 3, 4, 10.
253 Besteman *et al.*1999.
254 Nieuwhof 2020.
255 Kaspers 2020.

surrounding Wijnaldum, northern Westergo, had developed into the centre of a kingdom that covered the entire terp region of the northern Netherlands. According to Nicolay, the distribution of gold jewellery in a distinctive style suggests that the king residing at or near Wijnaldum had retainers across this entire area (see Section 3.13).[256] The evidence for glass working on the terp dates to this period and it seems likely that the elite status of the settlement played a role in attracting a travelling Merovingian beadmaker to visit the settlement.

Traces of habitation in this period are modest though and include the remains of six buildings divided over four households: four (possible) sod houses, two granaries and a sunken hut. Each house was built on a house platform built from sods. The houses were N-S orientated towards two large boundary ditches running east-west immediately south of the platforms. One (possible) house yielded evidence for two hearths and evidence for metal-working.

Wheel-thrown pottery imported from the Rhineland makes up 63.7% of the total ceramic assemblage on the terp during this period and it is thought that Wijnaldum or northern Westergo was a distribution centre for Merovingian pottery; traders of Frankish goods such as pottery (or its contents) may have depended on the Wijnaldum elite for access to markets in the northern coastal area.

The northern Netherlands became incorporated into the Frankish empire during the 8th century, an area equivalent to present-day Friesland in 734, and Groningen in 784 AD; northern Westergo was no longer the political centre controlling the area. An increasingly more even distribution of imported Carolingian pottery across the northern coastal area probably shows that traders were able to access the area and were no longer obstructed or controlled by the political centre. A reflection of this was the percentage of imported pottery at Wijnaldum during the Carolingian period, which increases to *c.* 13.3%. Habitation was concentrated in the south-eastern part of the excavated area of the site during the Carolingian period, on the southern flank of the terp. The highest parts of the terp were used as arable fields, also found on other terps during the 1st millennium.

Glass production waste: Glass-working evidence is sparse.[257] The most important object is a very thick fragment of baked clay, possibly part of a tray or a glass furnace, covered with a thick layer (1.0–1.3 cm) of weathered opaque yellow glass which has permeated through the porous, pinkish-orange fabric (fig. 3.15). It was found amongst waste from metal-working by a blacksmith/bronze-caster. The dump is very closely dated to the last quarter of the 6th and the first quarter of the 7th century and is contemporary with the glass-working evidence from the Jodenstraat site in Maastricht. Two small (flattened) globular beads of opaque yellow and white glass accompanied this find and are among the likely local products. This type of bead was also found among the bead production waste from the Jodenstraat site in Maastricht, where only yellow examples are represented.

Many glass beads found on the terp were in one of two large boundary ditches (550–600) and many of these simple, wound beads – including small flattened globular beads of opaque yellow,

Fig. 3.15 Wijnaldum-Tjitsma: Detail of possible furnace floor or tray with opaque yellow glass permeating through the fabric (Photograph: Henk Faber Bulthuis, Noordelijk Archeologisch Depot, Nuis).

256 Nicolay 2014, 20–23.
257 Sablerolles 1999, 263–266.

red and white glass – could have been local products.[258] Several halves of short cylindrical beads were retrieved from the above-mentioned large boundary ditch. They are split lengthwise, along the perforation, and are probably failed beads due either to overheating of the glass or as a result of not annealing the beads properly, causing them to crack (see Section 3.2.1). The same ditch also yielded three fragments of unworked amber, suggesting glass and amber bead-making could have been carried out at the same time.[259] An inhumation burial on the terp from 550–600 AD contained a necklace with at least 22 small, rather roughly shaped amber beads which were perhaps made locally.[260]

A transverse breaking splinter of an opaque greenish-white rod (see Section 3.2.1) comes from a 5th century context. It is, however, not securely dated, so perhaps this fragment is contemporary with the above-mentioned furnace or tray fragment. Moreover, almost all context-dated opaque white beads from the terp date to the second half of the 6th century or between 575 and 625.

In view of the paucity of the material, this production waste was interpreted as relating to just one production event. Because the glass waste production was found among that of a bronze-caster, it was suggested that bead-making could have been a secondary activity carried out by, for instance, a bronze-caster or a gold- or silversmith who visited the terp occasionally. The possibility of a travelling beadmaker, however, cannot be excluded as it would be logical for such a craftsman to seek out (more) permanent high-temperature craftsmen on the terp.

There is also some very limited evidence for bead-making on the terp in the Carolingian period. It consists of a fragment of translucent deeply coloured blue-green (turquoise) 'punty' glass from around a beadmaker's tool. It is from a context with a reliable date between 750–800.

An opaque yellow tessera from a ditch is probably dated between 750–770.[261] The tessera clearly shows thin swirling layers of colourless glass within the yellow matrix, indicating that the yellow opacifier is not fully homogenized with the translucent base glass (fig. 3.16).

Fig. 3.16 Wijnaldum: Opaque yellow tessera of opaque yellow glass streaked with colourless glass. The dimensions of the yellow tessera are: length 1.25 cm; height 0.81 cm and width 0.97 cm. (Photograph: Henk Faber Bulthuis, Noordelijk Archeologisch Depot, Nuis).

These two fragments do, of course, not constitute solid evidence for bead-making on the terp in the second half of the 8th century, but they at least raise the possibility, especially in view of the recently published tesserae finds from the terp of Wierum (see Section 3.13).[262]

3.13 Wierum, Groningen Province

Site: 19
Site type: Terp settlement
Province: Groningen
Municipality: Winsum
Place: Wierum
Toponym: Wierum
Start date: *c.* 400 BC
End date: late middle ages.
Description: The largest find of Roman tesserae in the Netherlands originates from the terp of Wierum near Wierumerschouw (Groningen Province) in the northern coastal region, which was a frequently flooded salt-marsh area.[263] The terp was located on the wide river Hunze, later renamed Reitdiep, which connected the Wadden Sea and North Sea with inland locations . The find is regrettably without a context and is likely to have been discovered between 1912 and 1916 when an estimated 3.5 ha of the original 5 ha of the site was dug commercially for its fertile soil. Only *c.* 1.5 ha of the original terp remained. In addition to the results of a coring programme, that provided information on the original circumference and the subsoil of the terp, in 1983 an overview of the finds was published.[264]

258 These finds come from boundary ditch 1233 (Sablerolles 1999, 270–273 passim).
259 Sablerolles 1999, 277, cat. nr 226–228.
260 Sablerolles 1999, 276, cat nr 191–213.
261 Sablerolles 1999, cat nr 216.
262 Crocco *et al.* 2021.
263 Nieuwhof 2006; Crocco *et al.* 2021 and references therein .
264 Miedema 1983.

In 2004 Groningen Province decided to restore the terp to its original size and shape using soil dredged from the river Reitdiep. Archaeological excavations carried out by the Groninger Instituut voor Archeologie (GIA) of the University of Groningen (Rijksuniversiteit Groningen) revealed that the site was inhabited from the 4th century BC or slightly earlier, until at least the late middle ages, probably with an interruption in the 4th century AD. Unfortunately, no farmhouses and outbuildings or artisanal areas were excavated. It is unlikely that there was much labour specialisation because Wierum was mainly a self-sufficient agricultural settlement, like all terps.

The find of a crescent-shaped gold pendant suggests that one of the retainers of the king who resided in or near Wijnaldum lived at Wierum in the Merovingian period (see Section 3.12).[265] During the 8th or possible the 9th century the region became incorporated into the Frankish empire. In the course of the Merovingian period a local leader may have made the settlement of Wierum his home. Because of its advantageous position on the river Hunze, it is surmised that by the Carolingian period it may still have had regional political significance. The combination of its convenient location and political status may have attracted itinerant craftsmen, including beadmakers.

Glass production waste: The assemblage has been interpreted as a supply of 'raw' glass of an early medieval glass beadmaker, most likely active on the terp in the 8th/9th century. This may have been a travelling beadmaker visiting terp sites such as Wijnaldum in the northern coastal region, which was most easily accessible by boat from the central riverine area with Dorestad at its centre.

The glass finds are dominated by (fragments of) 201 tesserae. Most tesserae are affected by heat: something which can be the result of having been in a high-temperature workshop environment. Other glass finds are made up of five fragments of highly coloured early Roman vessel glass, one fragment of possible naturally tinted Roman or early medieval vessel glass, three plano-convex drops of opaque green glass, almost colourless glass and translucent dark blue glass, and 13 irregular drops/melted lumps of (almost) colourless, pale green and pale blue-green glass. The latter may be recycled Roman vessel glass or Roman gold-foil tesserae stripped of their gold-foil. A small, matt grey sphere may be a globular glass drop of a type also found at bead-making sites of Maastricht-Rijksarchief (see Section 3.2.3), Wijk bij Duurstede (Dorestad) (see Section 3.4), and Åhus in Sweden.[266] Chemical analyses confirm the Roman date of the analysed glass finds.

Apart from the glass finds, the assemblage includes four stone tesserae: two of green porphyry, one of purple porphyry and a white tessera, probably white marble, which is still embedded in mortar showing it was robbed from an ancient mosaic. Three more tesserae show the remains of mortar adhering to one side. Furthermore, there is a fragment of Egyptian blue and two fragments of amber. The latter may indicate that the production of glass and amber beads was closely linked. Two fragments of basalt may derive from millstones imported from the Eifel. It is argued that the stone tesserae and the Egyptian blue pebble could have been collected accidentally with glass tesserae during the frequent spoliation of lavishly decorated Roman buildings. The Egyptian blue and highly coloured vessel fragments may even indicate that the collection originates from one or more buildings that contained a combination of first century AD shell mosaics, early glass mosaics and glass tesserae mosaics, or transitional forms thereof.

3.14 Deventer-Stadhuiskwartier, Overijssel Province

Site: 20
Site type: (Proto) urban settlement
Province: Overijssel
Municipality: Deventer
Place: Deventer
Toponym: Stadhuiskwartier
Start date: *c.* 850
End date: *c.* 1200 (thereafter medieval city)

Description: Deventer is situated in the east of the Netherlands, on the river IJssel, a tributary of the Rhine, which flowed into Lake Almere, now the IJsselmeer, which gave access to the Wadden Sea and the North Sea.

The excavations in the inner city of Deventer, project 312 (2007–2009) and project 434 (2012–2013) revealed multi-period occupation,

[265] Nicolay 2014.
[266] Preiß 2010, 124, 130 number 47; Callmer & Henderson 1991, Table 1C, 1.

including a late-mesolithic camp, late-prehistoric settlement traces and especially many remains of the medieval city and its early medieval predecessor.[267]

The earliest phase of the medieval settlement consists of several scattered buildings and a layer of arable land dating to the 8th and early 9th centuries. In the third quarter of the 9th century the land was reorganized on a large scale. The area was levelled and divided into new, regular plots. This development can be seen as the start of the process of urbanisation in Deventer. A new type of urban house was introduced which is clearly different from farmhouses in the surrounding agrarian settlements, e.g. they lack a stable. Many floor remains of this type of house were found, as well as a large number of cesspits, waste pits and wells. The finds indicate a large increase in craft activities in the late 9th century. At the end of the 9th century a defensive rampart was constructed around the settlement.

From the 10th century onwards several timber houses with cellars were present as well as secondary buildings with cellars which probably had an artisanal function. From the late 9th and 10th centuries there is evidence for bone-working, iron-working (smithing slags) and textile production from different locations. Production waste from different crafts is found together in the same waste pits on the same plots.

During the 10th and especially the 11th century large tuff (stone) houses appear. Initially, the tuff is sourced from old Roman building material, transported along the Rhine from the Roman fort at Xanten, Germany. In the late medieval period the area developed as the centre of the medieval city with a town hall and houses belonging to members of the urban elite.

The glass finds include vessel glass, window glass and some glass beads. Among the vessels are fragments of very thinly blown funnel beakers which are mostly made of a well-preserved, clear bluish-green glass. There are also fragments of thick-walled, curved vessels of heavily weathered glass. The window glass is mostly made of heavily weathered light glass that is greenish where it is possible to see the colour. Several quarries have preserved sides that were nibbled with a grozing iron in order to give them a distinct shape. The quarries would have been mounted in lead strips.

Glass production waste: Glass production waste is scanty and dates between *c.* 850 and *c.* 1050 (unpublished data). All glass production waste products were found in waste pits or cesspits. Two pits dating between 900 and 925 (project 312, K60 and K74) and two pits dating to the first half of the 9th century (project 343, K116 and K174) also yielded production waste of smithing, bone-working and textile production.

A hollow, glassy slag dates to 850–900 (434/16203) and is very similar to glassy slags found in a 10th century glass workshop in La Milesse (Sarthe, France) where wood ash glass was made from raw materials and blown into glass vessels.[268] Three fragments date between 900 and 925. A heavily weathered chip of glass with a conchoidal fracture and with characteristic concentric ribs (312/29057) was struck off a larger chunk of raw glass. A heavily weathered fragment has one convex surface and is more or less triangular in section (312/29028). It may be a transverse breaking splinter struck off a glass ingot with at least one curved side. A small, heat-affected fragment (312/29028) may be part of a pulled thread, but this is not certain.

Three glass production waste fragments date to the period 900–950. A small lump of translucent clear bluish-green raw glass (project 434/99144) has a conchoidal fracture and was struck off a larger chunk of raw glass. It is of a similar quality and colour to a funnel beaker fragment with optic blown oblique ribs (project 434/10380). A heavily weathered fragment with a triangular section (project 434/99154) is similar to fragment 312/29028 and may be a transverse breaking splinter. A heavily weathered fragment with two irregular, heat-affected surfaces (project 434/99154) could be a partially melted chip of raw glass.

An intriguing fragment (project 312/29048) dating to 950–1050 is difficult to interpret. It consists of two layers of translucent bright bluish-green and deep turquoise glass covered by a very thin film of opaque red glass. The fragment has two irregular surfaces which are heat-affected, probably as a result of being in a high-temperature glass workshop environment. The turquoise colour is very similar to that of a contemporary fragment of very thin flat glass, either window glass or a glass inlay with very fine grozing, from the same area (project 312/29063). A fragment of a deep turquoise quarry dating between 900–950

[267] All information about the excavations has been kindly provided by Emile Mittendorff, Project leader Archaeology, Deventer.

[268] Cf. Raux *et al.* 2015, Fig. 3F.

comes from another location (project 434 434/99139).

A knocked-off rim of a late Roman yellow-green cup of Isings type 96a[269] (project 434/ 99116) dated to 900–950 may be cullet intended to be melted down for the production of vessel or possibly window glass. It is not unusual to find old glass among early medieval glass production waste (see for instance Maastricht-Jodenstraat Section 3.2.1). An alternative explanation is that Roman glass was accidentally mixed in with Roman pottery (Samian ware) and tegulae fragments which are regularly found in Deventer in 10th–12th century contexts. It is thought that the tegulae and possibly (part of) the pottery had been transported to Deventer together with the Roman tuff that was reused to build stone houses. Part of the tegulae have stamps proving they were made in Xanten. There are as yet no indications for Roman habitation in Deventer.

269 Isings 1957, 113–114.

4 The materials, analytical techniques and methodology

4.1 Introduction

This chapter provides a brief introduction to the research samples studied and describes the analytical techniques used and methodology applied in the scientific analysis of the samples. The rationale of how the analytical data collected were used for the interpretation and comparison with previously published data is also explained.

4.2 An overview of the sites and glass samples

A detailed description of the evidence for the Dutch early medieval glass-working is given in Chapter 3.

One of the earliest sites providing glass for this project is Gennep in the province of Limburg. It is a 5th century AD Frankish settlement probably founded around 400 AD located on a high river terrace overlooking the confluence of the rivers Meuse and Niers. It is located between the late Roman fortress of Cuijk and the *burgus* of Asperden on the Niers to the east.[270] It did not yield any evidence for glass working. Some 200 glass vessels were found at the site which were mainly table ware, mostly drinking vessels. The samples analysed were all typical Frankish glass vessels consisting of bowls and cones.[271] They have provided critical compositional data for an early phase of the Dutch middle ages with which to compare other early medieval glasses.

Excavations on nine Merovingian sites mostly on the west bank of the river Meuse in Maastricht has produced some of the most comprehensive evidence for Early Medieval glassworking yet found in Europe. The best evidence for a glass industry was found during excavations at the Jodenstraat (MAJO) site in Maastricht (see Section 3.2.1). Evidence of glass bead making, including 38 fragments of crucibles containing opaque yellow and white glass were found with more good evidence from the Mabro site in Maastricht (see Section 3.2.2). Crucibles containing glass were sampled along with material from rods, bead fragments, splinters, drops and punty glass. Samples from both Jodenstraat and Mabro sites were analysed. Tables 4.1 and 4.2 are list of sampled crucibles from Jodenstraat and Mabro respectively, together with their photograph numbers provided here.

Table 4.1 Photographs of crucibles from Maastricht, Jodenstraat (MAJO) together with their sample numbers.

Sample	Sample number	Photo number
MAJO 1	20	figure appendix IV.11
MAJO 2	21	figure appendix IV.12
MAJO 3	22	figure appendix IV.13
MAJO 4	23	figure appendix IV.14
MAJO 5 (inside)	24	figure appendix IV.15
MAJO 5 (outside)	24	figure appendix IV.16
MAJO 6	25	figure appendix IV.17
MAJO 7	26	figure appendix IV.18
MAJO 8	29	figure appendix IV.19
MAJO 9	30	figure appendix IV.20
MAJO 10	39-40	figure appendix IV.21
MAJO 11	41	figure appendix IV.22
MAJO 12	42	figure appendix IV.23
MAJO 13	43	figure appendix IV.24
MAJO 14	44	figure appendix IV.25
MAJO 15	45	figure appendix IV.26
MAJO 16	46	figure appendix IV.27
MAJO 17	47	figure appendix IV.28
MAJO 18	50	figure appendix IV.29
MAJO 19	51	figure appendix IV.30
MAJO 20	52	figure appendix IV.31
MAJO 21	53	figure appendix IV.32
MAJO 22	54	figure appendix IV.33
MAJO 23	58	figure appendix IV.34
MAJO 24	60	figure appendix IV.35
MAJO 25	61	figure appendix IV.36
MAJO 26	68	figure appendix IV.37
MAJO 27	73-74	figure appendix IV.38

270 Brüggler 1994.
271 Sablerolles 1992; 1993.

Table 4.2 Photographs of crucibles from Maastricht, Mabro together with their sample numbers.

Sample	Sample number	Photo number
MABRO 1	7	figure appendix IV.1
MABRO 2	8	figure appendix IV.2
MABRO 3	9	figure appendix IV.3
MABRO 4	10	figure appendix IV.4
MABRO 5	11	figure appendix IV.5
MABRO 6	12	figure appendix IV.6
MABRO 7	13	figure appendix IV.7
MABRO 8	14	figure appendix IV.8
MABRO 9	15	figure appendix IV.9
MABRO 10	16	figure appendix IV.10

The Wijnaldum-Tjitsma (henceforth Wijnaldum) terp which has its heyday *c.* 550-650 AD when the area surrounding Wijnaldum, northern Westergo, had developed into the centre of a kingdom that covered the entire terp region of the northern Netherlands (see Section 3.12). Many beads, a tessera, vessel fragments, a rod and a possible furnace or thick tray fragment with opaque yellow glass adhering, were analysed.

Archaeological investigations of the proto-urban site at Utrecht dating to *c.* 700-10th century AD also produced 17 crucible fragments with glass adhering (probably 8th-9th century Carolingian pots) (see Section 3.5.1). These were found at the Domplein site and sampled for this project (a list if the crucible samples together with photo numbers are given in Table 4.3). In addition, scanty evidence for glass working was found at the Utrecht Oudwijkerdwarsstraat site dating to the 7th- first half of the 8th century AD. This glass was also sampled (Table 4.4). Excavations at the Carolingian site of Susteren-Salvatorplein (henceforth Susteren), a monastic site, produced two crucible fragments along with polychrome beads, windows and vessels (see Section 3.3).

Excavations of the famous emporium of Wijk bij Duurstede at the Hoogstraat and vicus sites (henceforth Dorestad) dating to between *c.* 600 and 900 AD produced a wide range of glass artefacts. Those selected for scientific analysis were mainly fragments of funnel beakers, bowls and bell beakers but also tesserae, linen smoothers.

Table 4.3 Photographs of crucibles from Utrecht, Domplein together with their sample numbers.

Sample	Sample number	Photo number
DOM 1	31	figure appendix IV.39
DOM 2	32	figure appendix IV.40
DOM 3	33	figure appendix IV.41
DOM 4	34	figure appendix IV.42
DOM 5	35	figure appendix IV.43
DOM 6	36	figure appendix IV.44

The latest site which produced glass included in this project was Deventer-Stadhuiskwartier (henceforth Deventer, see Section 3.14). The site dates to between *c.* 850 at the earliest and the 10th-11th centuries AD. Site excavations produced raw chunks of glass as well as vessel glass, glass beads and window glass.

The quantitative major and minor chemical composition and trace element chemical composition have been determined for each glass sample studied in this work. Altogether 279 glass objects have been sampled in this project. Neodymium and strontium isotopic compositions were determined for 20 glass samples which were selected based on their chemical characteristics. The major, minor and trace element compositions of our samples constitute the primary data for this project. The compositional group and/or formula group for each sample have been identified using certain compositional and isotopic characteristics. The technical details of the analytical methods used to produce chemical and isotopic data are elaborated below.

Table 4.4 Photographs of glassworking evidence from Utrecht, Oudwijkerdwarsstraat.

Sample	Sample number	Photo number
OUDWIJ 1	78	figure appendix IV.45
OUDWIJ 2	79	figure appendix IV.46

4.3 Electron probe microanalysis (EPMA) for major and minor chemical composition

Quantitative major and minor chemical compositions of our samples were determined on the JEOL JXA-8200 electron microprobe housed in Nanoscale and Microscale Research Centre, University of Nottingham. Fragments of each ceramic shard were mounted in cross-section in epoxy resin blocks and polished to a 0.25 mm diamond paste finish so as to reveal a fresh flat analytical surface. The blocks were carbon coated to prevent surface charging and distortion of the electron beam during analysis. The EPMA system is equipped with four wavelength-dispersive X-ray spectrometers with LIF, TAP, PETJ and LIFH crystals, a single energy dispersive X-ray spectrometer and both secondary and backscattered detectors. A defocused electron beam with a diameter of 40 µm was used so as to prevent volatilization of light elements such as sodium. The probe was run at an accelerating voltage of 15 kV and a beam current of 20 nA.

The system was calibrated with a mixture of mineral and oxide standards. A 'Phi-rho-z' correction program was used to quantify the results. The Corning B glass standard was routinely used as a secondary standard to check for accuracy and precision and to monitor any drift in the instrument. The analytical precision and accuracy achieved by using the Corning B standard are listed in Table 4.5

4.4 Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis for trace element compositions

The trace elemental compositions of our glass samples were determined using the LA-ICP-MS instrument consisting of either a NewWave UP193FX excimer (193 nm) or Elemental Scientific Lasers imageGEO (193nm) laser system and an Agilent 7500cs series instrument housed in the Analytical Geochemical Laboratories of British Geological Survey. The same samples used by EPMA major and minor chemical analysis are analysed for their trace element compositions. Prior to analysis the carbon coating of the samples was removed and the samples were cleaned by rubbing a tissue soaked in dilute acid over the surface for a few seconds. The sample was placed in a two volume ablation cell with a 0.8 L min^{-1} He flow. In addition to the sample block, NIST glass standards SRM610 and 612 as well as USGS glasses standards GSD-1G and BCR-2G were placed in the chamber. The UP193FX laser was fired for 40s at 10 Hz using a beam diameter of 70 µm; whereas the imageGEO was fired at 20Hz or 10s using a square 50 X 50 µm beam. Fluence and irradiance as measured by the internal monitor were typically 3 J/cm^2 and 0.85 GW/cm^2 respectively for both laser systems. With the UP193FX laser prior to introduction into the ICP-MS the He flow was mixed, via a Y-junction, with 0.85 L min^{-1} Ar and 0.04 L min^{-1} N_2 gas flows supplied by a Cetac Aridus desolvating nebulizer. The Aridus allowed introduction of ICP-MS tuning solutions and optimization of the Aridus sweep gas (nominal 4 L min^{-1} Ar). During solid analysis by the laser, the Aridus only aspirated air. The imageGEO system mixed the argon gas as above but added the N_2

Table 4.5 The recommended composition for the Corning B standard compared to average analytical results (n = 44) and associated standard deviations and errors using the electron microprobe.

	SiO_2	Al_2O_3	Na_2O	K_2O	CaO	TiO_2	FeO	MnO	MgO	CoO	CuO	P_2O_5	Sb_2O_5
Quoted	61.55	4.36	17	1	8.56	0.089	0.31	0.25	1.03	0.05	2.66	0.82	0.46
Measured	62.43	4.65	16.83	1.04	8.75	0.1	0.3	0.26	1.05	0.06	2.39	0.85	0.51
Standard deviation (n=44)	1	0.17	0.6	0.09	0.26	0.02	0.05	0.02	0.05	0.04	0.12	0.07	0.04
Error %	1.4	6.7	1	4	2.2	12.4	3.2	4	1.9	20	10.2	3.7	10.9

gas flow internally. Tuning was by rastering the laser beam over the glass standards.

The ICP-MS instrument was set for a dwell time of 7 ms for each of the 47 isotopes of interest to give one time-slice Data were collected in a continuous time resolved analysis (TRA) fashion as a repetitive series of time-slices. Prior to laser firing a period of at least 120 s of 'gas blank' was collected, then three ablations being made on the SRM610; three ablations on GSD-1G; 3 ablations on the SRM610; three ablations on the BCR-2G, 3three ablations on up to eight samples and finally three ablations on the SRM610; three ablations on GSD-1G. The SRM610 and GSD-1G were used to calibrate the system whilst the SRM612 and BCR-2G were used as a quality control (QC) materials. The full quality control report of our trace element analysis is listed in Table 4.6. Calibrations and data reduction were performed using Elemental Scientific Lasers Iolite4 software, with data compilation in Microsoft Excel 2016.

The nature of laser ablation means that there is some variability in ablation volume and transport efficiency with different materials (matrix effects). Therefore, accepted practice is to normalize results to an internal standard element; in the current study Si was chosen for this purpose with its concentration being known in the NIST glasses and provided by the EPMA data for the study glasses.

The 26 trace element pattern has been used in many recent publications to identify pristine natron glass of different compositional types. We have adopted this approach here in the discussion of our results below.

4.5 Thermal ionization mass spectrometry (TIMS) analysis to determine Nd and Sr isotopic compositions

For isotopic analysis, a small glass fragment was first sampled and transferred to a clean (class 100, laminar flow) working area for further preparation. In the clean laboratory, the samples were cleaned ultrasonically in Milli-Q water, dried on a hotplate and then weighed into pre-cleaned Teflon beakers.

For Sr isotopic analysis, the samples were spiked with ^{84}Sr tracer solution and dissolved in Teflon distilled 8M HNO_3 and Ultrapure 29M HF. Samples were converted to chloride form using Teflon distilled 6M HCl. The samples were then taken up in calibrated 2.5M HCl and centrifuged. Strontium was collected using Eichrom AG50 X8 resin columns. Each sample was then loaded on to a single Re filament with TaF, following the method of Birck.[272] The ^{87}Sr/^{86}Sr and Strontium elemental concentrations were determined by Thermal Ionization Mass spectroscopy (TIMS) using a Thermo Triton multi-collector mass spectrometer at the National Environmental Isotope Facility of the British Geological Survey. The international standard for ^{87}Sr/^{86}Sr, NBS987, loaded in the same way, gave a value of 0.710259 ± 0.000018 (n = 21, 2σ) during the analysis of these samples, and sample data was normalized to the accepted value for this standard of 0.710250. Procedural blank values were in the region of 100 pg.

For Nd isotopic analysis, fractions were dissolved in 1 ml of 2% HNO_3 prior to analysis on a Thermo-Electron Neptune mass spectrometer, using a Cetac Aridus II desolvating nebulizer. 0.010 L min^{-1} of nitrogen were introduced via the nebulizer in addition to argon in order to minimize oxide formation. The instrument was operated in static multi-collection mode, with cups set to monitor ^{142}Ce, ^{143}Nd, ^{144}Nd, ^{145}Nd, ^{146}Nd, ^{147}Sm, ^{149}Sm, and ^{150}Nd. 1% dilutions of each sample were tested prior to analysis, and samples diluted to *c.* 20 ppb. Jet sample cones and X-skimmer cones were used, giving a typical signal of *c.* 800–1000 V/ppm Nd. Correction for ^{144}Sm on the ^{144}Nd peak was made using a ratio for ^{147}Sm/^{144}Nd derived from multiple analyses of SpecPur© samarium solution. This correction was insignificant due to the efficiency of the column separation. Data are reported relative to ^{146}Nd/^{144}Nd = 0.7219. The Nd standard solution JND-i was analysed during each analytical session and sample ^{143}Nd/^{144}Nd ratios are reported relative to a value of 0.512115 for this standard.

272 Birck 1986.

Table 4.6 Summary of quality control (QC) data for analysis of glass samples.

Reference material: SRM612		Number of analyses=101	Nuber of analytical sessions=3			
Element	**Measured isotope**	**Expected concentration (mg/kg)**	**Mean concentration (mg/kg)**	**Standard deviation**	**RSD%**	**Error%**
Li	7	39.5	40.2	1.5	3.8	-2
B	11	37.3	34.3	2.7	7.2	9
Na	23	99780	103858	1867	2	-4
Mg	24	58	68	4	7	-15
Al	27	11102	11167	295	3	-1
P	28	73	46.6	152	208	56
K	31	53	62.3	4	8	-15
Ca	39	84382	85002	2298	3	-1
Ti	42	39.8	44	4	9.9	-9
V	47	37.8	38.8	1.5	3.9	-3
Cr	51	34.8	36.4	1.7	4.8	-4
Mn	52	38	38.7	1	4	-3
Fe	55	46	51	3	7	-11
Co	56	34.3	35.5	0.9	2.7	-3
Ni	59	37.7	38.8	1.4	3.7	-3
Cu	60	36.7	37.8	1.2	3.3	-3
Zn	63	37.6	39.1	2.2	6	-4
As	66	33.2	35.7	2.2	6.5	-7
Rb	75	31.3	31.4	0.8	2.5	0
Sr	85	76.9	78.4	2.9	3.7	-2
Y	88	38.4	38.3	1.1	3	0
Zr	89	38.5	37.9	1.1	2.9	2
Nb	90	38.3	38.9	1.2	3.2	-2
Mo	93	35.6	37.4	1.6	4.6	-5
Sn	95	37.6	38.6	1.6	4.1	-3
Sb	120	33.6	34.7	1	3.1	-3
Cs	121	41.2	42.7	1.1	2.6	-3
Ba	133	38.7	39.3	1	2.5	-1
La	138	35.7	36	0.9	2.6	-1
Ce	139	37.7	38.4	1.2	3.3	-2
Pr	140	37.3	37.9	1.2	3.3	-2
Nd	141	34.9	35.5	1.4	4	-2
Sm	146	37.3	37.7	1.5	4	-1
Eu	147	35	35.6	1.3	3.6	-2
Gd	153	37.7	37.3	1.4	3.7	1
Tb	157	36.6	37.6	0.9	2.6	-3
Dy	159	35.6	35.5	1.1	3.1	0
Ho	163	37.8	38.3	1	2.6	-1
Er	165	38.4	38	1	2.7	1
Tm	166	36.6	36.8	1.1	2.9	-1
Yb	169	38	39.2	1.2	3.2	-3
Lu	172	36.6	37	0.9	2.5	-1
Hf	175	37	36.7	1.2	3.4	1
Ta	178	36.9	37.6	1	2.6	-2
Pb	208	38.2	38.6	1.1	2.9	-1
Th	232	37.5	37.8	1.2	3.1	-1
U	238	36	37.4	1.2	3.4	-4

4.6 How analytical data is used in this study

The type of glass whether natron, plant ash or wood ash, can be easily identified by major and minor oxide contents such as Na2O, K2O, CaO and MgO. The majority of the glass studied here is natron glass; wood ash glass and plant ash glass only account for a small fraction of the samples. One of the main aims of this study is to categorize the majority which are natron glasses according to different compositional types (see Section 2.4.1). These are related to their provenance, so we can gain an insight into raw glass supply in the early medieval Netherlands. Because a large number of samples are involved in this study, the job of categorizing natron glass samples into compositional groups has mainly been achieved by using three plots, $Al2O_3/SiO_2$ against $TiO_2/Al2O_3$, Pb against Sb, and a 26 trace element pattern.

Firstly the Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot is used to provide a preliminarily classification of natron glasses into compositional groups: TiO_2, Al_2O_3 and SiO_2 essentially represent the heavy mineral, feldspar and quartz contents of the sands used for making the glass,[273] which can reflect their provenance very well (Figure 4.1).[274] The Pb against Sb plot is used to show the levels of impurities brought in by recycling of the glass samples. In 'pristine' (non-recycled) natron glass the levels of a few correlated elements such as Pb, Sb and Cu are very low, but for recycled glass the levels of these elements are much higher. Pb and Sb (both in ppm) are the most consistent demonstrators among these elements, so they have been chosen to distinguish 'pristine' glass samples from recycled glass samples.

The criterion for the identification of a 'pristine' glass is that the Pb and Sb contents are both under 1000 ppm, following previous conventions.[275] The compositional groups of 'pristine' glass samples identified using the two previously mentioned plots are then confirmed by using the 26 trace element patterns of the samples. Although it has been found that the rare earth element patterns of all natron glasses tend to be very similar, when lighter trace elements (excluding some elements which may have been introduced with the colourant, such as transition metals) are included, the patterns of the four main different compositional groups, HIMT *sensu stricto*, Foy 2, Egyptian II and Levantine,[276] can be distinguished very well (Figure 4.2).[277] The 26 trace elements used in this study are V, Cr, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Th, U, and their normalized concentrations compared to that for the upper continental crust.[278].

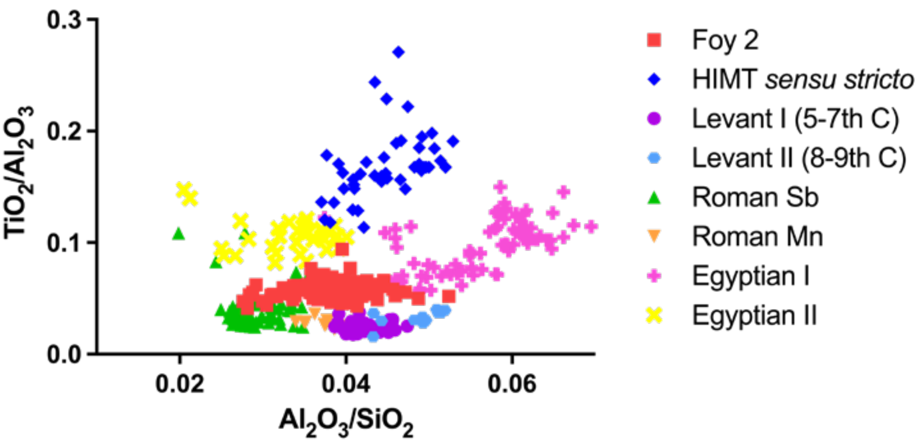


Figure 4.1 Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot showing the compositional differences between major groups of natron glasses.

273 Freestone *et al.* 2018.
274 Data sources: Foy *et al.* 2003 (HIMT sensu stricto, Levantine I), Schibille, Sterrett-Krause & Freestone 2016 (Foy 2), Schibille *et al.* 2019 (Egyptian I and Egyptian II), Freestone *et al.* 2015 (Levantine II), Silvestri, Molin & Salviulo 2008 (Roman Mn and Roman Sb).
275 Foster & Jackson 2009.
276 The trace element patterns of Levantine I glass and Levantine II glass are very similar. Thus only the pattern of Levantine I glass is shown here to demonstrate its difference with that of other compositional groups. It is difficult to distinguish Egyptian I glass and HIMT *sensu stricto* glass by their trace element patterns. This it is not too much of a problem here since Egyptian I glass is not a significant compositional group in northwestern Europe.
277 Schibille, Sterrett-Krause & Freestone 2016; Bertini, Henderson & Chenery 2020.
278 Kamber *et al.* 2005.

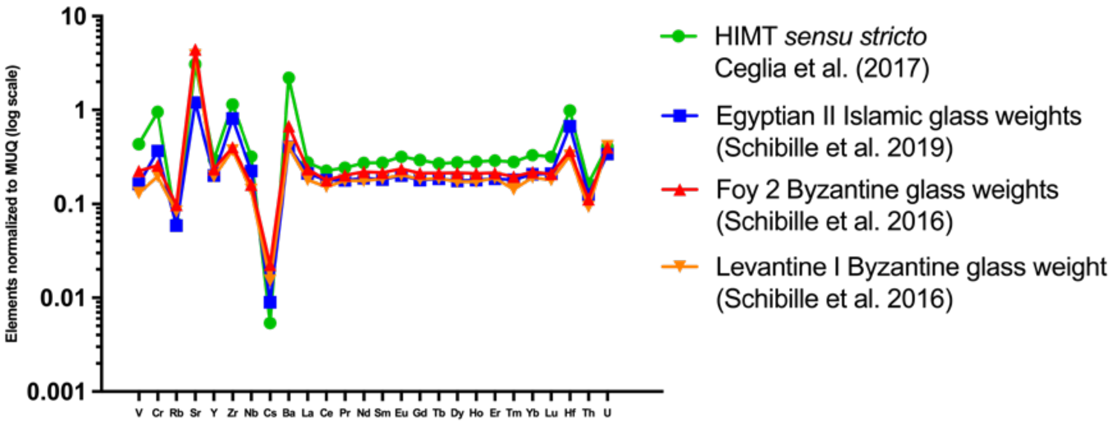


Figure 4.2 The 26 trace element patterns of four major compositional groups of natron glass. The trace elements are V, Cr, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Th and U

5 The analytical results and discussion

5.1 Introduction

Glass samples from nine sites were studied, including two sites in both Maastricht and Utrecht. In this chapter the chemical compositional features of glass samples from each site will be elaborated separately. The major and minor chemical compositions of analysed samples are given in Appendix II. The trace element data of analysed samples are given in Appendix III.

5.2 Glass samples from Maastricht (Jodenstraat and Mabro sites)

Apart from two glass vessel fragments and three window glass fragments, which may be glass cullet, all the rest of the 51 glass samples from Jodenstraat are the remains of on-site bead making, and they all came from one pit filled between late 6th century and early 7th century AD.[279] The glass samples from the bead-making context can be roughly divided into three groups: translucent naturally coloured and cobalt blue glass waste, highly coloured opaque glass, and vitreous materials attached to crucibles (Appendix I).

5.2.1 Naturally coloured and cobalt blue bead-making glass waste

The bead-making glass waste from Jodenstraat includes glass drops, glass rods, punty glass, glass fragments and glass attached to crucibles. Because of the shape and state of the glass samples found in the bead-making context, and the similarity of their chemical compositions with that of the glass beads, it has been suggested that bead making involved firstly colouration of the naturally coloured base glass followed by further procedures to make the glass into beads.[280] If this suggestion stands, the bead-making glass waste should reflect the chemical features of the base glass used by the bead makers. Their low K_2O and MgO and elevated Fe_2O_3, TiO_2 and MnO contents suggest that they can all be categorized as the so-called HIMT natron glass dominating northwest Europe during the 4th–7th century. HIMT glass is a general name for early medieval natron glass with elevated Fe_2O_3, TiO_2 and MnO contents (see Section 2.4.1).

There are some further compositional groupings that can be demonstrated by the ratios of TiO_2, Al_2O_3 and SiO_2, which represent essentially the heavy mineral, feldspar and quartz contents of the sands used for making the glass. In Figure 5.1 we can see that the naturally coloured and blue glass waste from Jodenstraat forms one tight group, and it agrees very well with the well understood Foy 2 compositional group of natron glass (compare with Figure 4.1), including one of the crucible fragments with pale green glass attached (Joden 29) which is least

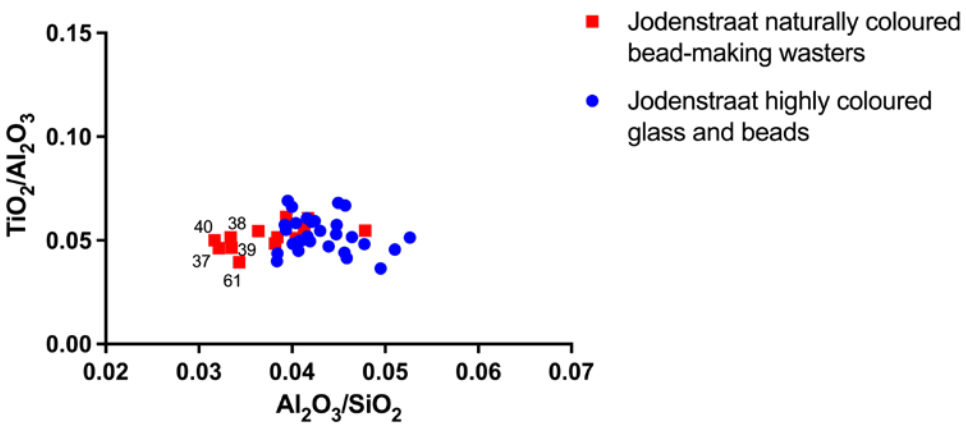


Figure 5.1 A plot of Al_2O_3/SiO_2 versus TiO_2/Al_2O_3 for Jodenstraat naturally coloured bead-making waste and highly coloured opaque glass and beads.

[279] Sablerolles, Henderson & Dijkman 1997.
[280] Sablerolles, Henderson & Dijkman 1997.

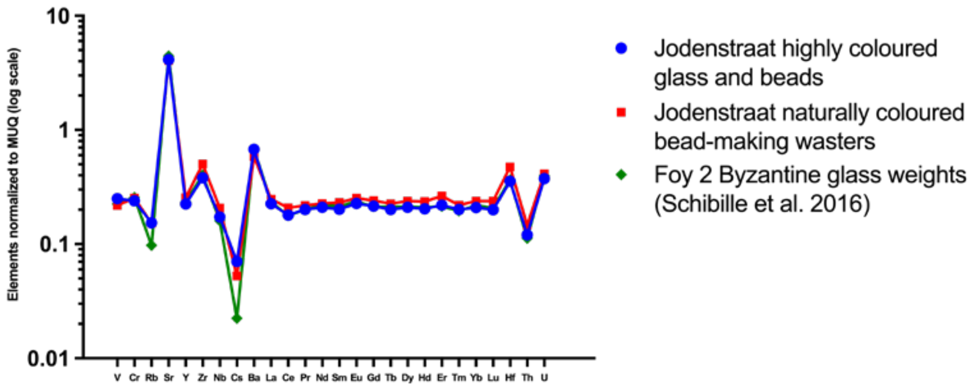


Figure 5.2 The 26 trace element patterns for Jodenstraat naturally coloured and blue bead-making waste and Jodenstraat highly coloured opaque glass and beads compared to that of Foy 2 glass.

contaminated. The latter shows no evidence that lead or tin had been added (yet). The slightly elevated PbO contents of some naturally coloured glass waste may have been caused by contamination during the production process since lead was an important raw material ingredient in bead making of this period in northwestern Europe. The elevated PbO content of early medieval glass could also indicate glass recycling.[281] However, the Sb contents, which are correlated with PbO in recycled early medieval glass, and often used together with PbO as an indicator of glass recycling, are all very low at ≤1000 ppm level.

Therefore we are more inclined to believe that this glass waste is 'pristine' glass rather than recycled, and that the elevated PbO was introduced during the production procedure. The 26 trace element pattern in the naturally coloured and blue glass waste from Jodenstraat agrees very well with that for Foy 2 glass published previously (Figure 5.2) confirming that they are Foy 2 glass. Amongst the bead making waste there is a group of five blue samples: four blue fragments (Joden 37-40) and one translucent blue coloured bead fragment (Joden 61). In the Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot, these five samples locate in the area of Foy 3.2, one of the two subgroups of Foy 2, the other subgroup being Foy 2.1 (see Section 2.4.1). The flat tapered bead fragment (Joden 61) does not contain elevated PbO, nor is it opacified with SnO_2 like the many other highly coloured beads found at Jodenstraat. The four cobalt blue fragments (Joden 37-40) and the cobalt blue bead (Joden 61) have the same composition which suggests this type of non-tin opacified blue beads was made directly from 'pristine' cobalt blue coloured raw glass.

5.2.2 Highly coloured opaque glass

The highly coloured glasses found at Jodenstraat are beads, rods and drops, potentially all linked to the process of bead making. These highly coloured glass samples are in four basic colours: yellow, white, red and greenish-blue. They all have elevated PbO contents ranging from a little over 2.0 wt% to over 40 wt% PbO, which demonstrates that lead was used as one of the key raw materials in bead making in addition to natron glass. As shown in figure 5.3, the average PbO contents in these yellow, white, red and greenish-blue glasses are not quite the same especially for yellow glass: its PbO contents are much higher than that of the other three colours. The reason for the different PbO concentrations in yellow glass and in other colours is addressed in detail in Section 5.10.3 below.

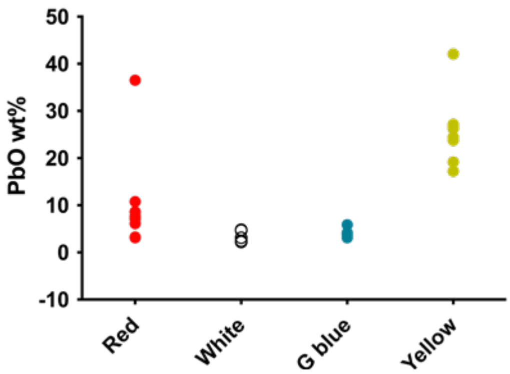


Figure 5.3 The PbO contents of highly coloured opaque glasses from Jodenstraat (G blue = greenish-blue).

281 Foster & Jackson 2009.

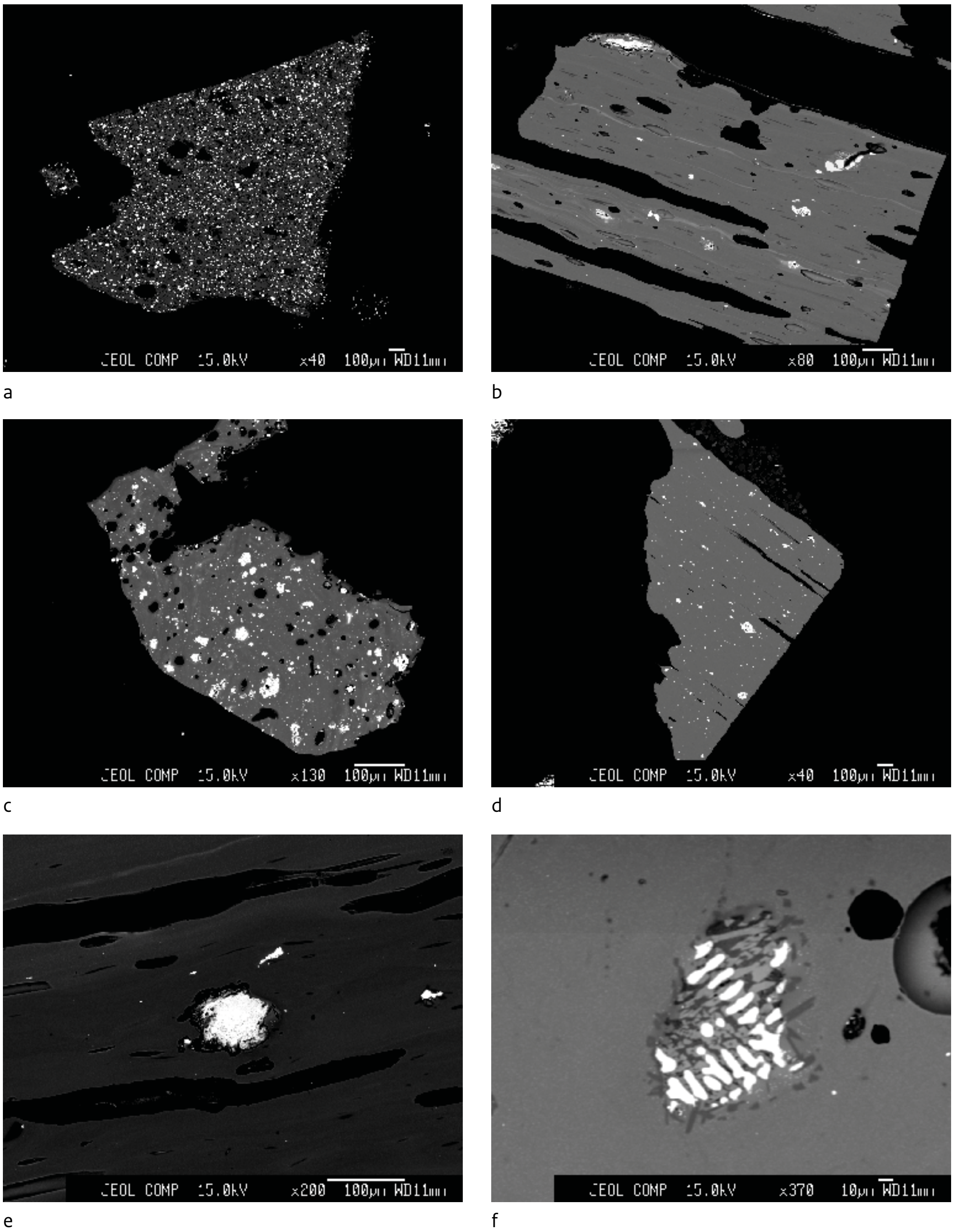


Figure 5.4 Backscattered SEM images of yellow (top left: 5.4a), green (top right: 5.4b), white (middle left: 5.4c), red (middle right: 5.4d) coloured glass from Jodenstraat and crystalline inclusions: SnO_2 opacifiers found in white, green and red colour glass (bottom left: 5.4.e), ground fayalitic slag surrounded by 0 valence micron sized particles in red glass (bottom right: 5.4f).

From the backscattered SEM images of the highly coloured opaque glass samples from Jodenstraat (Figure 5.4), we can see that they all contain some highlighted (pale grey) inclusions of variable sizes. The quantitative EPMA analyses of these phases show that they differ compositionally. The typical chemical compositions of the three crystalline phases of different highly coloured glasses are listed in Table 5.1. According to their quantitative chemical compositions and backscattered SEM images, the crystalline phases in yellow glass can be identified as lead tin yellow II ($PbSn(Si)O_3$) with a $PbO/(SnO+SiO_2)$ ratio of about 2:1 (Figure 5.4). Lead tin yellow II was widely used as the colourant in yellow coloured beads in early medieval Europe.[282] Three types of crystalline inclusions are found in the glass matrix of the red coloured glass (Figure 5.4): firstly a phase containing SnO_2 of 50–70 wt% and variable SiO_2 and PbO contents; secondly, a high iron phase, which was also observed in similar medieval red colour beads from England and identified as ground fayalitic slag;[283] finally, micron sized particles of 0 valence metallic copper, which are scattered evenly in the glass matrix.

282 Heck, Rehren & Hoffmann 2003.
283 Peake & Freestone 2012.

Table 5.1 The typical chemical compositions of the three crystalline phases found in Jodenstraat highly coloured glasses.

	Lead tin yellow II	SnO2 opacifiers	Fayalitic slag
SiO_2 (wt%)	8–18	15–30	10–25
Al_2O_3 (wt%)	1–3	2–3	<1
Na_2O (wt%)	3–5	5–8	1–5
K_2O (wt%)	-	-	-
CaO (wt%)	-	1	-
SnO_2 (wt%)	15–24	50–70	-
PbO (wt%)	60–65	2–15	<1
FeO (wt%)	-	-	65–90

According to previous studies we can conclude that the phase containing SnO_2, the dominant composition, acts as the opacifier in the glass matrix. The red glass is mainly coloured by micron sized particles of 0 valence copper, like many other types of red glass and ceramic glazes,[284] and the ground fayalitic slag would have acted as an internal reducing agent during the formation of the copper particles.
The crystalline inclusions found in the white glass and the greenish-blue glass beads are the same (Figure 5.4), and they also contain the first type of inclusion found in the red glass, mainly SnO_2 at 50–70%, with variable SiO_2 and PbO % levels, acting as the opacifier in the glass matrix. The amount of SnO_2 found in the white glass is much higher than that found in the red and greenish-blue glass, producing its opacified white colour. The colour of the greenish-blue glass is caused by a copper based colourant (CuO), as indicated by high copper contents, which would have dissolved in the glass matrix so it cannot be observed as a separate phase in the SEM images.

In the plot of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (Figure 5.1), Jodenstraat highly coloured opaque glass samples form a tight cluster in the area of the Foy 2 compositional group (with Figure 4.1 as reference), located slightly to the right of the cluster of Jodenstraat colourless bead-making waste. In Fig. 5.2 it can be seen that the 26 trace element pattern of the averaged composition of these highly coloured glass samples is identical with that of Jodenstraat colourless bead-making waste and the Foy 2 pattern published previously. Additionally, the Sb contents of all highly coloured opaque glass samples from Jodenstraat are also very low at ≤1000 ppm, the same as found in naturally coloured and blue bead-making waste found on the site. These results indicate that the base glass of Jodenstraat highly coloured opaque glass is also 'pristine' Foy 2 glass and that the bead-making debris formed during the production process was produced using this same base glass.

The observation that Jodenstraat highly coloured opaque glasses generally have higher Al_2O_3 contents than the bead-making waste, demonstrated by their clustering to the right of colourless bead-making waste in Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot (Figure 5.1), can be attributed to the addition of the lead tin yellow II colourant and tin opacifiers during the colouring process: the lead tin yellow II colourant and tin opacifiers have higher Al_2O_3/SiO_2 than the base glass (Table 5.1).

5.2.3 Vitreous and semi-vitreous materials attached to the crucibles

From twelve crucibles retrieved from the bead-making context of Jodenstraat, three types of vitreous materials attached to them have been examined scientifically. They are naturally coloured natron glass (two samples), naturally coloured glass mixed with bright yellow residues (eight samples), and a white melt with a light yellow tinge (two samples). The description of the vitreous residues attached to each crucible is listed in Table 5.2.

Naturally coloured natron glass has been found attached to crucibles Joden 21 and Joden 29 from the bead-making context of

[284] Bandiera *et al.* 2020.

Jodenstraat, and their chemical compositions have been discussed along with other naturally coloured glass in Section 5.2.1: they conform to a Foy 2 composition.

The naturally coloured glasses mixed with bright yellow residues in 8 crucibles turned out to be very pure lead oxide-silica glass. The Na_2O concentrations are very low in these lead glasses (Appendix II), which shows that natron glass was not involved in the procedure that produced these lead glasses and the yellow/white residue mixture. Yellow residues attached to crucibles from early medieval northwest European sites have been studied before[285] and the analytical results for yellow residues attached to crucibles from Jodenstraat are the same, namely lead tin oxide.

Chemical compositions and SEM images show that the main phase of the bright yellow lead tin residue is lead tin yellow II ($PbSn(Si)O_3$) (Figure 5.5a), where the ($SnO+SiO_2$) to PbO weight ratio is close to 1:2. It has been suggested that these crucibles containing lead tin yellow residues are evidence of on-site production of the yellow colourant which was then added to base glass during the manufacture of yellow beads.[286] The chemical compositions and SEM morphologies of the lead tin yellow II crystallites attached to the Jodenstraat crucibles are very similar to the lead tin yellow II found in the yellow glass beads and yellow bead-making debris from Jodenstraat. Therefore we also suggest that these crucibles are remains of on-site lead tin yellow colourant production, and that the lead tin yellow II produced in the crucibles would have been used directly to colour the base glass to create a yellow colour. More details regarding the procedures of on-site lead tin yellow II production and how the crucibles were used during the process are addressed in Section 5.10.2 below.

A white melt with a light yellow tinge has been found attached to two crucibles (Joden 23 and Joden 30). Their chemical compositions show that this white melt also contains SnO_2, PbO and SiO_2 as the main components, but that their weight ratios are quite different from that of lead tin yellow II (Appendix II). SnO_2 is the dominant component, ranging from 50 wt% to 70 wt% in different areas of the white melt; the PbO and SiO_2 contents are variable. The SEM morphology of the tin white crystallites is also quite different from that of lead tin yellow in that no lead silica glass surrounds the tin oxide in the former whereas it does in the latter (Figure 5.5b).

Table 5.2 Description of the vitreous residues attached to Jodenstraat crucibles

Sample number	Vitreous residue description
Maastricht-Jodenstraat 19	lead yellow ii surrounded by pure lead glass
Maastricht-Jodenstraat 20	lead yellow ii surrounded by pure lead glass
Maastricht-Jodenstraat 21	natron glass
Maastricht-Jodenstraat 22	pure lead glass with small yellow spots
Maastricht-Jodenstraat 23	white melt
Maastricht-Jodenstraat 24	pure lead glass with small yellow spots
Maastricht-Jodenstraat 25	pure lead glass with small yellow spots
Maastricht-Jodenstraat 26	pure lead glass with small yellow spots
Maastricht-Jodenstraat 27	lead yellow ii surrounded by pure lead glass
Maastricht-Jodenstraat 28	lead yellow ii surrounded by pure lead glass
Maastricht-Jodenstraat 29	natron glass
Maastricht-Jodenstraat 30	white melt

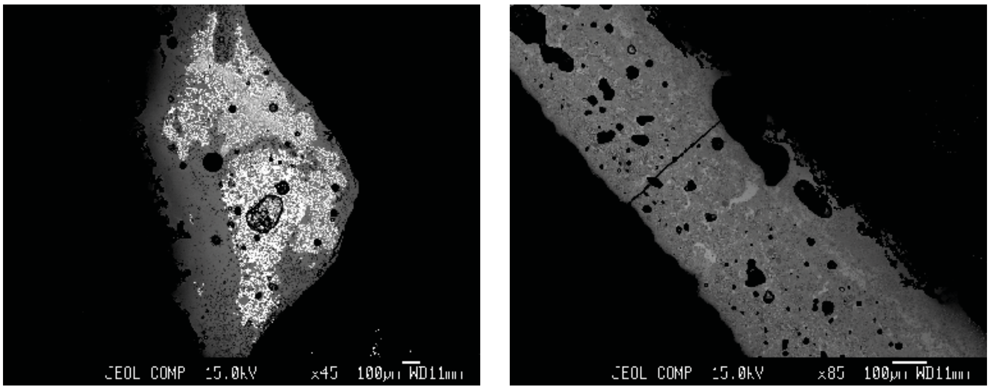


Figure 5.5 Backscattered images of yellow residue (left: 5.5a) and white melt (right: 5.5b) found attached to crucibles from Jodenstraat.

285 Henderson & Ivans 1992; Heck, Rehren & Hoffmann 2003; Peake & Freestone 2014.

286 Heck, Rehren & Hoffmann 2003; Peake and Freestone 2014.

Moreover, the chemical compositions and SEM morphologies of this tin white melt are very similar to that of the tin opacifiers in white, red and greenish-blue beads. Therefore, we think these white melts attached to crucibles are evidence for on-site production of tin opacifiers in early medieval northwestern Europe, and they constitute the first such evidence to be reported. More details of the separate production of the tin white opacifier at Jodenstraat is addressed in Section 5.10.3 below.

5.2.4 Glass artefacts

Five glass samples from Jodenstraat, three window glass fragments (Joden 44–46) and two glass vessel fragments (Joden 60, 68), may be cullet. The elevated MnO, Fe_2O_3 and TiO_2 contents suggest that they are HIMT natron glass. Their Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios show that the window glass (Joden 46) belongs to the HIMT *sensu stricto* compositional group, samples 44, 45 and 60 distribute in the area of the Foy 2 compositional group and sample 68 could be a piece of Roman glass (Figure 5.6a with Figure 4.1 as reference). The form of Joden 68 also suggests that it is a Roman vessel fragment (thick naturally coloured ribbed green glass), but it does not have high Mn or high Sb contents normally found in decolourized and green Roman glasses.[287]

The Sb and Pb contents of the five glass samples show that apart from Joden 60, which has Sb and Pb contents over 1000 ppm, the balance have low Sb and Pb contents <1000 ppm (Figure 5.6b). Therefore, this result shows that Joden 60 was made using recycled glass while the other four samples were made from un-recycled ('pristine') glass. The 26 trace element patterns of Joden 45 and Joden 46 confirm that they have the same patterns as Foy 2 and the HIMT *sensu stricto* respectively published previously, but the trace element pattern of Joden 44 shows some clear differences from that of the Foy 2 glass pattern which may be related to the unusually high MnO content (1.9%) in the sample (Figure 5.7a).

5.2.5 Crucibles from the Mabro site, Maastricht

Ten crucibles with vitreous residues attached from the Mabro site in Maastricht, which is located very close to Jodenstraat, were also analysed here. Lead tin yellow II surrounded by pure lead silica glass has been found in two crucibles, Mabro 12 and Mabro 14. 'Mixed alkali' glass was found attached to crucible Mabro 7, a high potassium oxide glass containing grey mainly angular unmelted silica grains was found attached to crucible Mabro 9 (Figure 5.8), though both are contaminated with 7.2 and 7.9% aluminium oxide, and high iron and titanium oxide. In Figure 5.8 the body of the glass is the homogenous pale grey layer on the right-hand side.

The glass in crucible 9 contains 13% K_2O but low levels of MgO and P_2O_5 so it is unlikely to be evidence for working wood ash glass. Moreover, it contains 7.54% Al_2O_3 and 3.49% Na_2O. The presence of angular unmelted SiO_2 grains and high Al_2O_3 suggests that what remains is the interaction layer with the crucible fabric. The mixed alkali glass in crucible 5 contains levels of MgO and phosphorus pentoxide that are significantly lower than in typical mixed

[287] Silvestri, Molin & Salviulo 2008.
[288] Pactat *et al.* 2017.

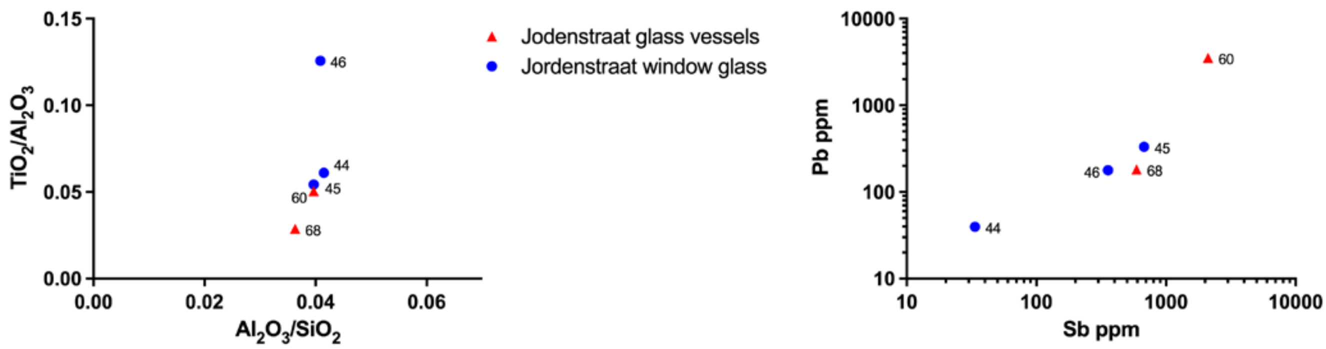
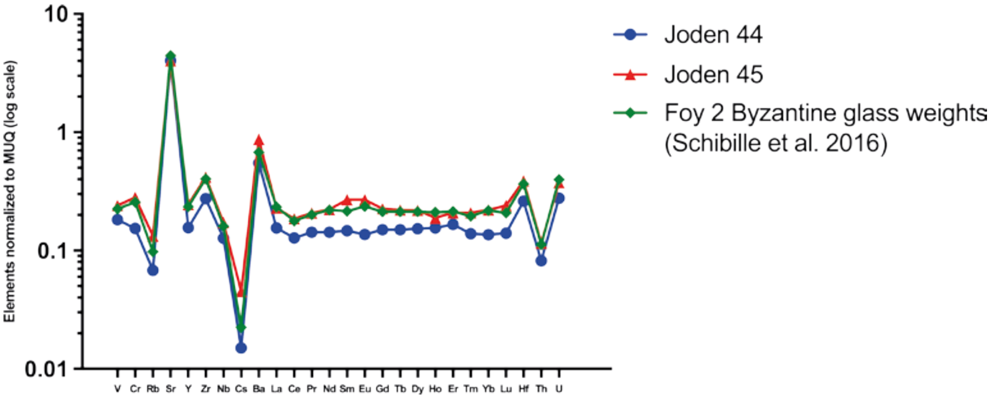
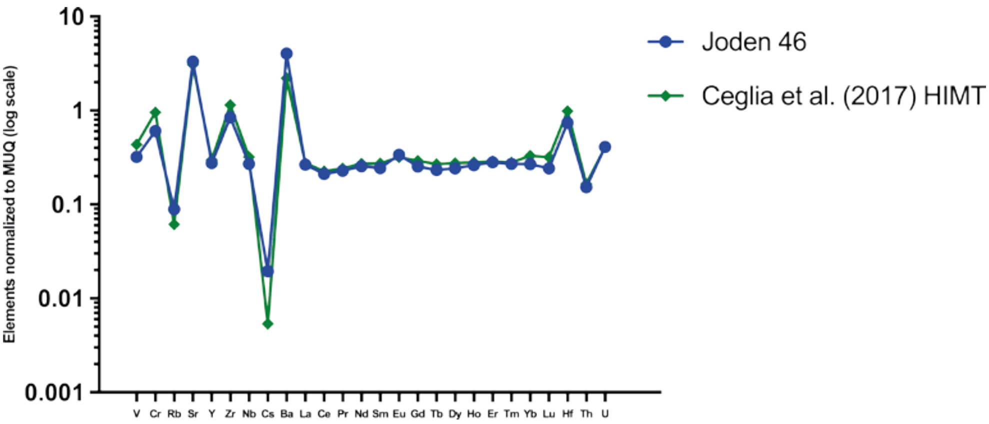


Figure 5.6 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Jodenstraat glass artefacts.



a



b

Figure 5.7 The 26 trace element patterns for Joden 44–45 compared to that of relevant natron glass types published previously (top: 5.7a) and the same for Joden 46 (bottom: 5.7b) (Joden= Jodenstraat, Maastricht).

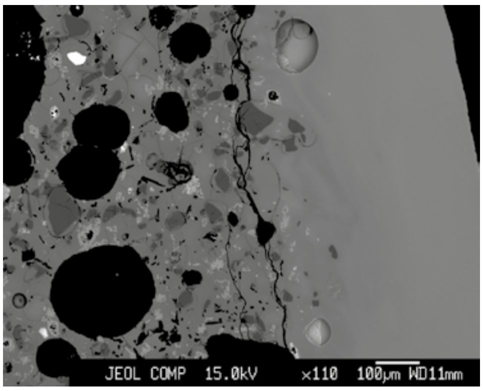


Figure 5.8 Backscattered SEM image of glassy residue attached to crucible Mabro 9.

alkali glasses, such as those from Méru in France.[288] It is therefore more likely to be a contaminated natron glass.

Soda glass with an unusual chemical composition was found attached to five crucibles: Mabro 8 and Mabro 11 contain high Al_2O_3 contents at 9.87% and 12.48% respectively as well as high iron and titanium interpreted as contamination by interaction with the crucible fabric. They may therefore be contaminated natron glasses. Mabro 13, Mabro 15 and Mabro 16 have higher CaO contents at 6.74%, 7.52% and 5.82%, approaching normal levels for natron glass. Although Mabro 13 and 15 contain relatively high Cl levels at 0.52% and 0.38% they contain normal levels of alumina, iron and titanium. All three contain elevated K_2O levels of up to 2.6% but these are not paired with elevated magnesia. The elevated K_2O levels may be due to contamination.

No vitreous phase was found in Mabro 10. Analysis of the 'frit-like' material on the rim of crucible 11 dating the late 4th-early 5th century shows that it is a fuel ash slag with no detected CaO, high Cl (0.32%), high K_2O (4.56%) but relatively low MgO (1.15%), high Fe_2O_3 (2.9%) and high MnO (0.98%). Paynter has shown that melting a natron glass in wood fired furnace can lead to fuel ash slags and contaminated glass of highly variable compositions.[289]

5.3 Glass samples from Gennep

The 28 vessel glass fragments from Gennep are the earliest glass studied here: they are tightly dated to between the late 4th century and mid-6th century AD. Their low K_2O and MgO contents and elevated MnO, TiO_2 and Fe_2O_3 contents suggest that they are all a type of HIMT natron glass. The TiO_2/Al_2O_3 and Al_2O_3/SiO_2 ratios of Gennep glass show that seven of them locate in the area of the HIMT *sensu stricto* compositional group (Ge 44 and Ge 45 fall in the overlapping area of HIMT *sensu stricto* and Egyptian I compositional groups) and 21 of them cluster closely in the area of the Foy 2 compositional group (Figure 5.9a with Figure 4.1 as reference). Pb and Sb concentrations are both <1000 ppm and are used here as the criterion to provide a preliminary distinction between 'pristine' glass from recycled glass. According to this criterion, 12 out of the total 28 samples can be regarded as 'pristine' glass: six of them belong to the HIMT *sensu stricto* group and the other six belong to the Foy 2 group (Figure 5.9b).

The 26 trace element patterns of the six 'pristine' HIMT *sensu stricto* glass samples are essentially identical and their average pattern is very similar to that of HIMT glass reported previously thus confirming their HIMT compositional type (Figure 5.10a).[290] The 26 trace element pattern of the average composition of the six 'pristine' Foy 2 glass is also identical with the Foy 2 glass pattern reported previously (Figure 5.10b).

It has been suggested that the recycling of Roman tesserae and coloured vessel glass to supplement the dwindling supply of natron glass in northwestern Europe started approximately in the early 8th century, which is signified by the elevated Sb and Pb contents of glass in this period.[291] However, our Gennep vessel glass samples are securely dated to late 4th to mid-6th century AD, and we already see elevated Sb and Pb contents for the majority of them (17 out of 29).

5.4 Glass samples from Wijnaldum

Apart from two pieces of evidence for bead production, one greenish-white glass rod splinter (WIJ 41) and one turquoise punty glass (WIJ 42), the rest of the 40 glass samples from Wijnaldum can be separated into three groups: highly coloured opaque glass beads, colourless glass beads (four out of five were metal foil and the other one was trail-decorated) and glass vessels.

5.4.1 Highly coloured opaque glass beads

The highly coloured glass beads are in three basic colours: opaque yellow, opaque white and opaque red. Wijnaldum beads share a similar

[289] Paynter 2008.
[290] The trace element patterns of HIMT glass and Egyptian I glass are very similar, so we are unable to further categorize the two samples which plot in the overlapping area of HIMT glass and Egyptian I glass, Ge 44 and Ge 45, into a more specific compositional group using trace elements.
[291] Freestone 2015.

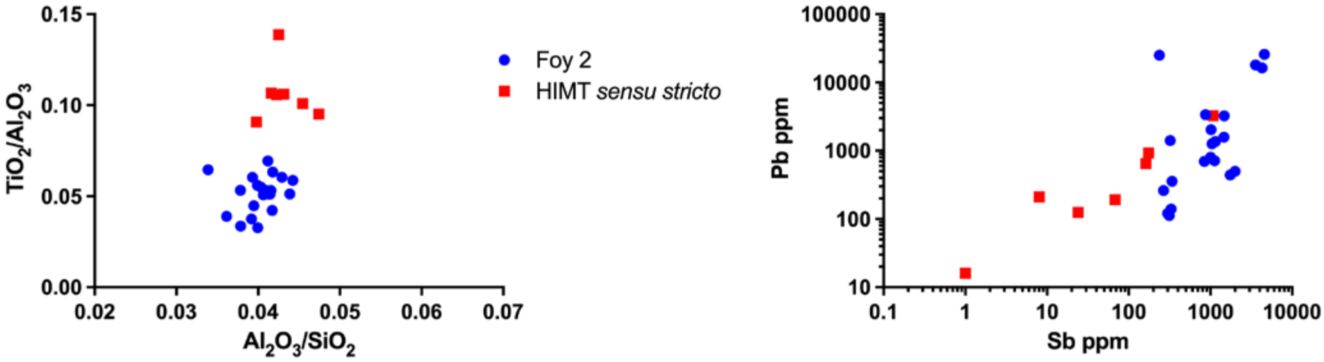
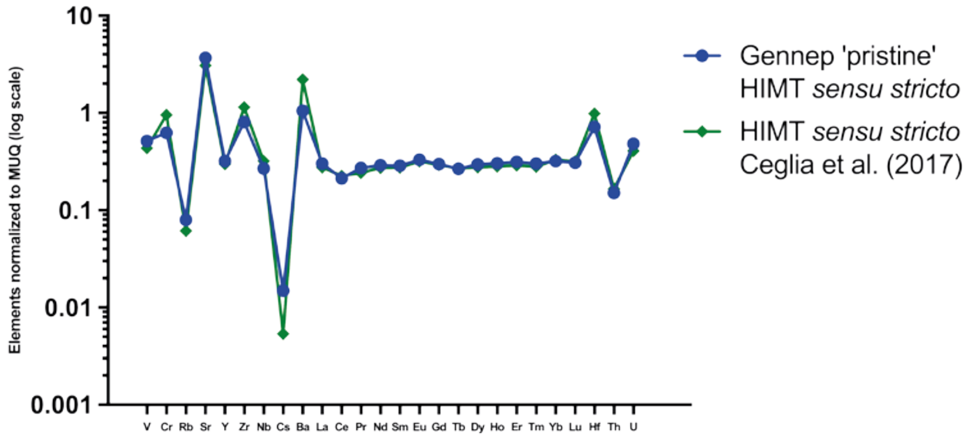
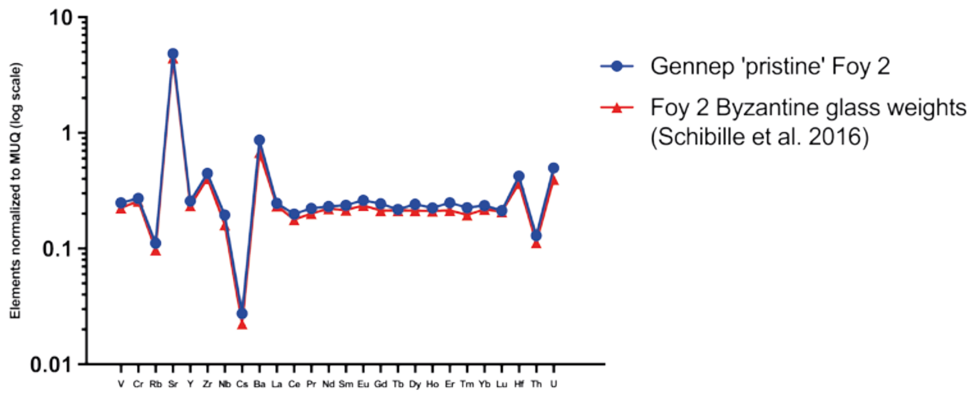


Figure 5.9 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Gennep glass vessels.



a



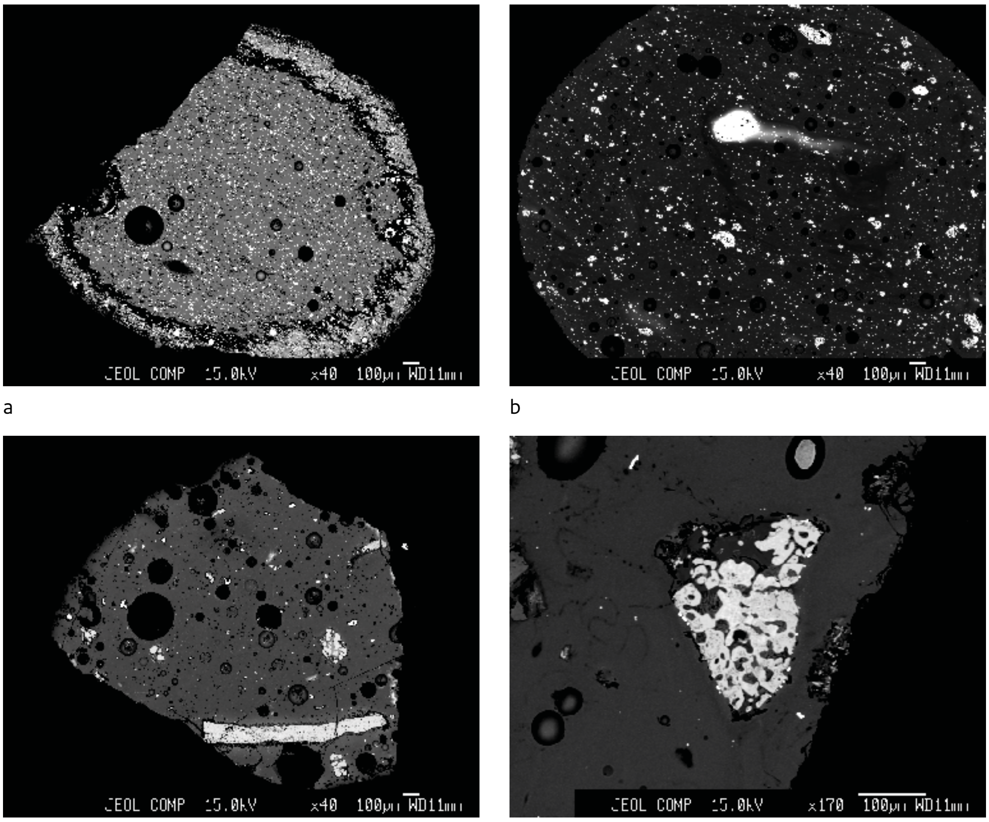
b

Figure 5.10 The average 26 trace element patterns of Gennep ‘pristine’ HIMT *sensu stricto* glass and ‘pristine’ Foy 2 glass compared to that of relevant natron glass types published previously (top: 5.10a) and the same for Gennep ‘pristine’ Foy 2 (bottom: 5.10b).

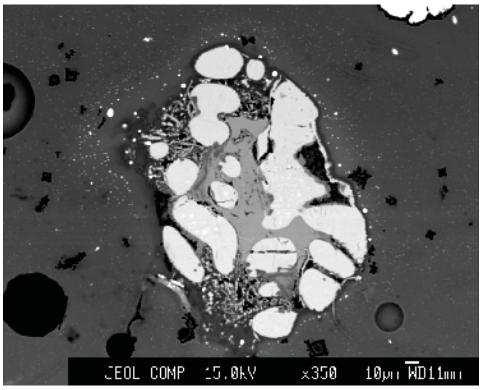
date to Maastricht Jodenstraat beads, and the chemical compositions of glass beads are also very similar. First of all, the highly coloured glass beads from Wijnaldum all have elevated PbO contents: 23–56% in yellow beads, 3–23% in red beads and 1–5% in white beads. Secondly, they share the same compositional feature of low Sb contents as found in Jodenstraat opaque beads: all highly coloured beads from Wijnaldum have a Sb content of <1000 ppm. Moreover, the colouring mechanisms of Wijnaldum beads are the same as for Jodenstraat beads. The Wijnaldum yellow beads are coloured by lead tin yellow II; the Wijnaldum white beads and red beads are opacified by tin oxide; and the Wijnaldum red beads are coloured by micron sized copper particles with iron-rich fayalitic slag acting as an internal reducing agent (Figure 5.11). The glass working tray covered with a contaminated opaque yellow vitreous layer was analysed previously (see section 2.4.2).

5.4.2 Colourless glass beads

The five colourless glass beads are a special group (WIJ 35–39), not seen in Maastricht. Unlike highly coloured opaque glass beads, they do not have elevated PbO contents. Since their Sb and Pb contents are all under 1000 ppm, it suggests that ‘pristine’ rather than recycled glass was used to make them. Among the five colourless glass beads, WIJ 35 (a gold foil bead) and WIJ 37



a b c d



e

Figure 5.11 The backscattered images of a Wijnaldum yellow bead (top left: 5.11a), white bead (top right: 5.11b), red bead (middle left: 5.11c), tin opacifiers found in white beads and red beads (middle right: 5.11d) and fayalitic slag surrounded by 0 valence copper micron particles found in red beads (bottom: 5.11e).

(a silver foil bead) have completely different chemical compositions from glass vessels and other glass beads from Wijnaldum. Their lower Na_2O and CaO contents and higher K_2O and MgO contents compared to natron glass indicate that they are plant ash glasses, they date to between 775 and 900 AD according to their context dates and this correlates with the introduction of plant ash glasses in western Asia by Islamic glass-makers.

The low MgO and K_2O contents and elevated Fe_2O_3, TiO_2 and MnO contents of the other three colourless glass beads (a gold foil bead and a silver foil bead dating to 450-550, and a colourless bead with red streaks dated to 750-850) suggest they were made from a type of

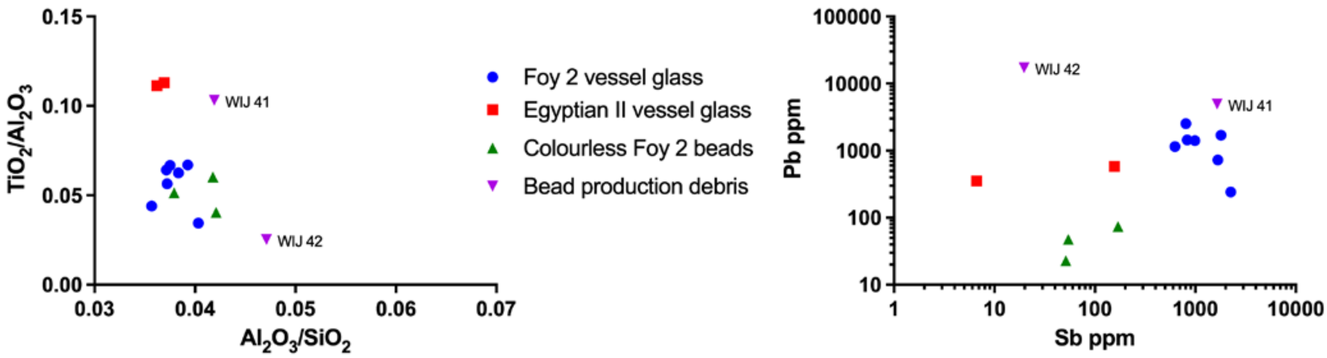
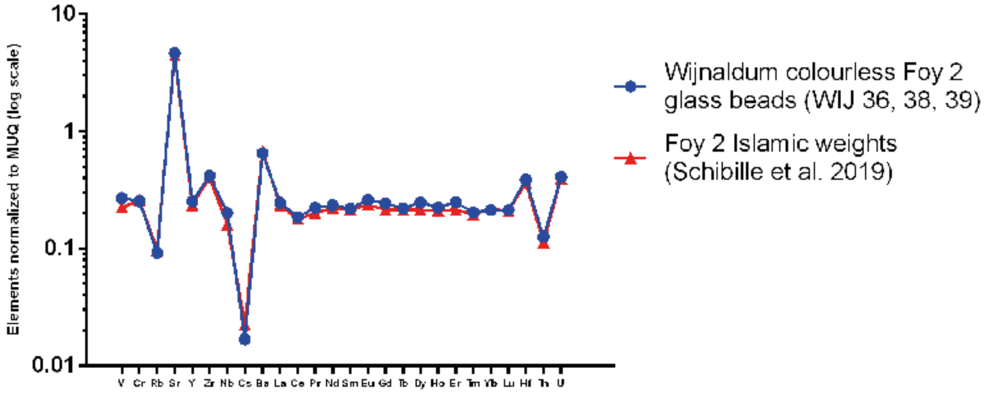
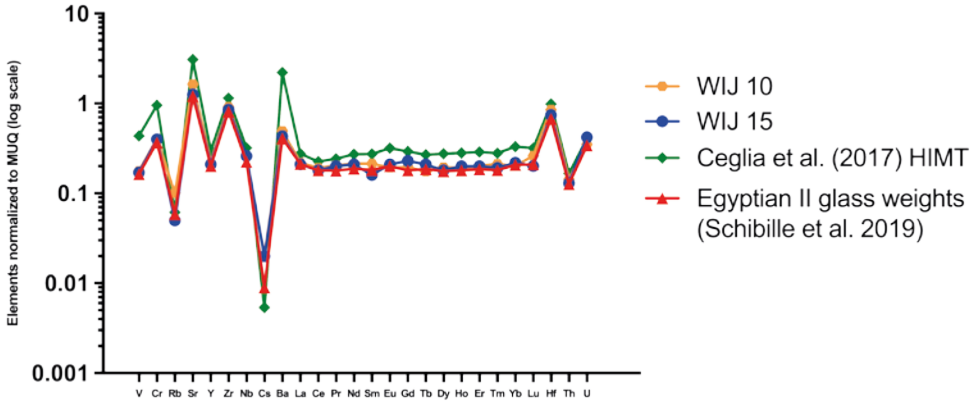


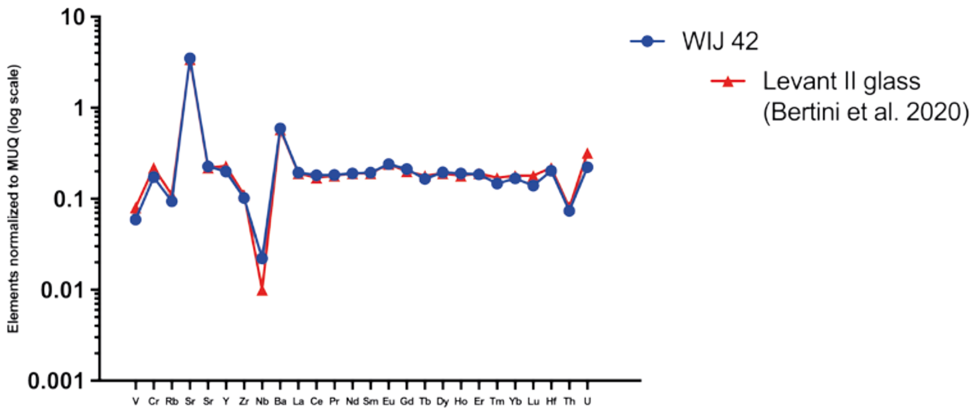
Figure 5.12 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Wijnaldum glass samples.



a



b



c

Figure 5.13 The 26 trace element pattern for colourless Wij 36, 38 and 39 compared to that of relevant Foy 2 glass published previously (top: 5.13a), for Wij 10 and 15 compared to that of relevant HIMT and Egyptian II glasses published previously (middle: 5.13b) and Wij 42 compared to that of relevant Levantine II glasses published previously (bottom: 5.13c) (Wij = Wijnaldum).

HIMT natron glass; their Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios show that they belong to the Foy 2 compositional group (Figure 5.12a with Figure 4.1 as reference). The Sb and Pb contents of the three Foy 2 beads are all very low at <200 ppm, so this suggests that they were made from ‘pristine’ Foy 2 glass rather than from recycled glass (Figure 5.12b) and two are early examples of this kind of glass. The 26 trace element pattern of the average composition of the three beads confirms this suggestion (Figure 5.13a).

5.4.3 Vessel glass

The nine vessel glass samples from Wijnaldum are dated between the mid-5th century and late 9th century. The low MgO and K_2O contents of these samples show that they are all made from natron glass. Their Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios show that WIJ 10 and WIJ 15 plot at the overlapping zone of HIMT and Egyptian II compositional groups while the other seven samples belong to the Foy 2 compositional group (Figure 5.12a with Figure 4.1 as reference). Their Pb and Sb levels are both <1000 ppm and can be used as a criterion to distinguish pristine glass from recycled natron glass in a preliminary way. We can see that WIJ 10 and WIJ 15 can both be regarded as 'pristine' glass, while all Foy 2 glass samples are recycled glass (Figure 5.12b). The 26 trace element patterns for WIJ 10 and WIJ 15 resolve the inconclusive identification of the two samples using major chemical compositions which suggested that they are Egyptian II glass or HIMT *sensu stricto* glass. The trace element patterns of WIJ 10 and WIJ 15 show a close resemblance to that of Egyptian II glass with clear compositional differences from that of HIMT *sensu stricto* glass (Figure 5.13 middle). Therefore we can confirm that WIJ 10, a blue green funnel beaker, and WIJ 15, a dark blue funnel beaker with an incalmo rim, were made from 'pristine' Egyptian II glass. The dates of WIJ 10 (800–850 AD) and WIJ 15 (770–900 AD) are also consistent with the suggested dates for when Egyptian II glass was in circulatation in the 8th–9th centuries AD, a time when the supply of pristine Levantine glass was drying up.[292]

5.4.4 Bead production materials

The high Na_2O content and low K_2O and MgO contents in the greenish-white rod splinter (WIJ 41) and turquoise punty glass (WIJ 42) suggest that they are both natron glass. However, their different Fe_2O_3 and TiO_2 contents and Al_2O_3/SiO_2, TiO_2/Al_2O_3 ratios suggest that they do not belong to the same compositional group. WIJ 42 has quite low Fe_2O_3 and TiO_2 contents of 0.45% and 0.08% respectively, a feature that differs from the dominating HIMT natron glass discussed here, and the Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios suggest it can be categorized as having a Levantine II (8th–9th century) natron glass composition (Figure 5.12a with Figure 4.1 as reference); the 26 trace element pattern for WIJ 42 confirms this identification (Figure 5.13c).

The established date for this compositional group agrees with the date provided from the archaeological context (750–800 AD). The high CuO content in WIJ 42 shows that the turquoise colour was caused by copper. The greenish-white glass rod splinter WIJ 41 has elevated TiO_2, Fe_2O_3 and MnO contents like most of the natron glass studied in this work. The Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios of WIJ 41 plot at the overlapping area of HIMT *sensu stricto* and the Egyptian II compositional groups (Figure 5.12a with Figure 4.1 as reference). The elevated Sb and Pb contents of WIJ 41, with 1650 ppm and 4933 ppm respectively, suggest that it was made from recycled glass (Figure 5.12b).

5.5 Glass samples from Utrecht

Nine samples from two sites in Utrecht were analysed. Three glass fragments derive from Utrecht Oudwijkerdwarsstraat which dates to the 7th to mid-8th century AD. Six crucible samples (Utr 31–36) are from Utrecht Domplein which dates to between the mid-8th to late 9th century AD. The three glass fragments from Utrecht Oudwijkerdwarsstraat (Utr 77–79) are soda lime glasses. Utr 77, a fragment with a yellow tinge and Utr 79, a piece of green debris from glass working are natron glasses. Utr 78 has a modern composition and therefore will not be discussed further.

In the plot of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (Figure 5.14a with Figure 4.1 as reference), Utr 77 plots in the area of the Foy 2 compositional group, while Utr 79 plots in the area of Roman glass. Utr 79 contains high CaO and slightly high Cr_2O_3. The Sb content of Utr 77 is low at 70 ppm, but its Pb content is high at 4034 ppm, suggesting it is a recycled glass. Both Sb and Pb contents of Utr 79 are low at <1 ppm and 92 ppm respectively, consistent with the Sb and Pb contents of non-Sb-decolourized Roman glass (Figure 5.14 right).

Glass attached to six crucible fragments from Utrecht Domplein was also investigated. There is a thin very pale green, appearing colourless, glass layer attached to crucibles Utr 31 and Utr 32. There is evidence from the chemical compositions that the glass had interacted with the body of the crucible: they contain 12.6% and 4.65% Al_2O_3 respectively. Utr 31 especially has levels of Fe_2O_3 (3.17%) and TiO_2 (0.64%) very likely to be the result of these elements migrating into the glass from the crucible fabric at high temperatures. Utr 31 was probably

292 Phelps *et al.* 2016.

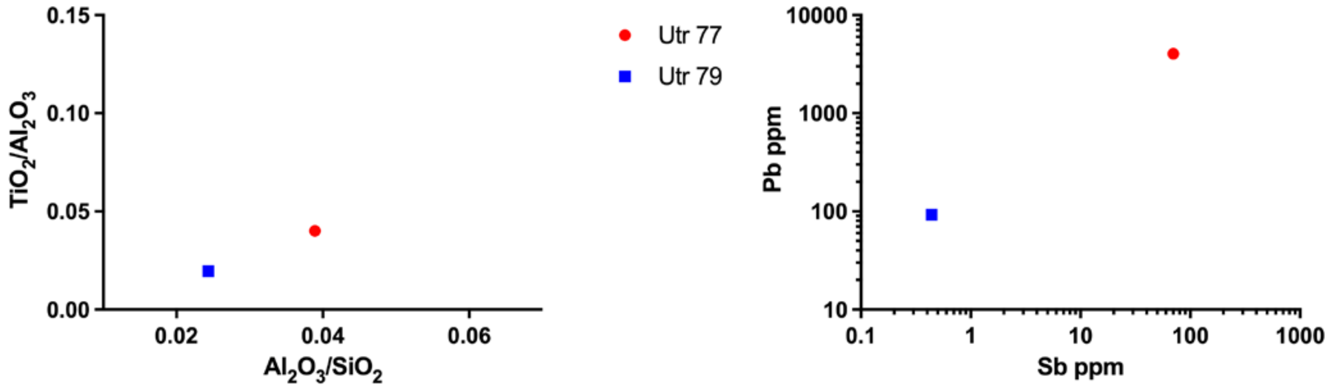


Figure 5.14 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Utr 77 and Utr 79 (Utr = Utrecht).

originally a soda glass; a high level of K_2O (4.73%) (yet only 0.57% MgO) is probably also due to contamination. A high level of antimony (0.45% Sb_2O_3) is difficult to explain but could be due to glass recycling.

Utr 32 contains 1.66% MgO, 1.9% K_2O, 15.54% Na_2O and 5.75% CaO, all characteristics of a plant ash glass. However, a very low level of P_2O_5 (0.06%) is unusual for a plant ash glass.

The thick layer of green and red striped glass in crucible Utr 34 from Utrecht Domplein also warrants more detailed discussion. It contains 1.45% MgO and 1.42% K_2O, levels that are probably consistent with a natron glass, as well as a probable uncontaminated level of Al_2O_3 (2.82%). However it also contains 0.56% P_2O_5 as well as 4.91% PbO, 0.9% SnO_2, 0.615% CuO and 1.5% Fe_2O_3. The copper in the red glass would be in a reduced form (Cu_2O) and also the iron; the lead, tin and iron were probably introduced as part of the colouring process along with the copper. This composition is similar to red coloured glass from Maastricht Jodenstraat and Wijnaldum. It also contains 0.728% MnO and 0.12% CoO. The levels of MgO and K_2O are below 1.5% and fall within the values for a natron glass, yet the phosphorus level would be more in line with a plant ash glass and may indicate a degree of contamination. Red streaks of decoration are sometimes found in early medieval vessel glass. It can be assumed that it was produced deliberately by mixing in small amounts of red glass or red glass colorant.

Number 33 is too contaminated to be able to discern the original chemical composition of the glass, with an Al_2O_3 level of 36.89%. The greenish glasses in crucibles 35 and 36 also contain a mismatch between the potassium and magnesium oxide levels as well as elevated antimony. Number 36 contains 5.4% K_2O and 8.21% Na_2O so it is tempting to suggest this might be a mixed alkali glass. However, the relatively low level of MgO (0.84%) suggests that the high K is due to contamination of the glass. Both 35 and 36 contain high levels of Al_2O_3 at 7.41% and 7.68%, so again this shows that contamination has occurred. They contain 1.1% and 0.39% CuO probably originally added as colourants to a natron glasses.

5.6 Glass samples from Wijk bij Duurstede (Dorestad)

Apart from one raw glass chip, five tesserae fragments, one opaque yellow glass rod and two linen smoother fragments, the other 55 glass samples from Dorestad are all glass vessel fragments dated to between the mid-8th and mid-9th centuries, and do not derive from a glass-working context.

5.6.1 Vessel glass

Apart from two wood ash glass samples (Dor 103 and Dor 136), a yellow-green palm funnel and an iridescent yellow-green funnel beaker base the low K_2O and MgO contents and elevated Fe_2O_3, MnO and TiO_2 contents of the rest of the 52 vessel glass samples from Dorestad suggest they are all made from natron glass. Their Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios show that apart from Dor 122, a pale green funnel beaker, which can be categorized as Egyptian II glass, the other 51 samples cluster closely in the area the Foy 2

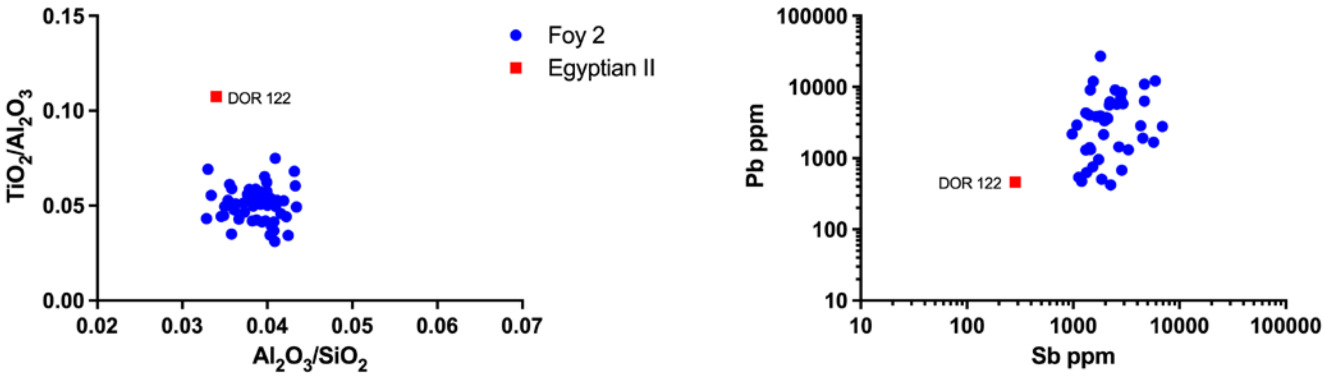


Figure 5.15 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Dorestad vessel glass samples.

compositional group (Figure 5.15a with Figure 4.1 as reference). Apart from Dor 122, all the rest of the natron glass vessels have either Sb contents >1000 ppm or Pb contents >1000 ppm and mostly both (Figure 5.15b). This suggests these glass vessels were generally made from recycled glass rather than 'pristine' glass.

Dor 122 is the clear exception in this assemblage. Not only does it belong to a different glass compositional group (Egyptian II), its low Sb and Pb contents, 285 ppm and 461 ppm respectively, also suggest it could have been made from 'pristine' glass (Figure 5.15b): the 26 trace element pattern for Dor 122 confirms that it is Egyptian II glass (Figure 5.16). The date of Dor 122 (9^{th} century AD) is also consistent with the suggested date for when Egyptian II glass was in circulation, in the 8^{th}–9^{th} centuries AD.

The two wood ash vessel glass samples (Dor 103, a palm funnel and Dor 136, a funnel beaker base) have quite similar chemical compositions. Their CaO contents are very high at over 13%, their K_2O and MgO contents are significantly higher than that found in natron glass at over 7% and their Na_2O contents are low at below 2%. Such compositions are quite typical of relatively early wood ash glass, even if the K_2O levels are quite low for such glass.[293]

5.6.2 Other glass

The two dark green linen smoothers (Dor 150, 151) have a very peculiar composition. They have high lead contents at around 22% and high Al_2O_3 contents at around 7%. Their high CaO, P_2O_5, MgO and K_2O contents also suggest they could have been made from wood ash as a main ingredient. Over a hundred linen smoothers were found at an important medieval Viking city, Hedeby in northern Germany.[294] Analytical work shows that they are generally of two glass compositions: wood ash glass and wood

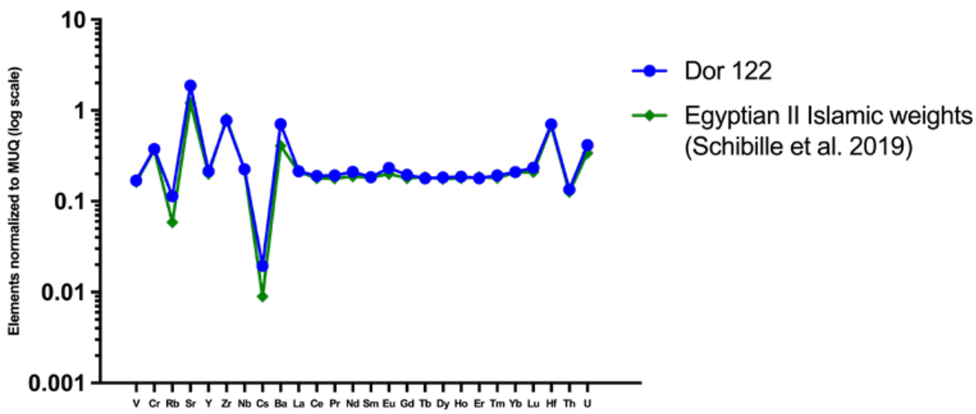


Figure 5.16 The 26 trace element pattern for Dor 122 compared to that of relevant Egyptian II natron glasses published previously (Dor=Dorestad).

[293] Wedepohl and Simon 2010
[294] Krüger & Wedepohl 2003.

ash-lead glass. Our linen smoother samples are wood ash-lead glass, similar to those from Hedeby. Although the presence of the two linen smoothers could result from Viking trade a clear compositional match with slag resulting from the refinement of lead-silver ores at the Carolingian mine of Melle demonstrates that, along with many other linen smoothers found in France, Ireland, Germany, Norway Denmark and Belgium, the origin of the vitreous slag used to make them was Melle.[295]

It has been suggested that the glass working carried out in the important trading *entrepôt* of Dorestad was based on remelting tesserae, imported raw glass and glass rods (see Section 3.4). A raw glass chip from the site has a typical Foy 2 natron glass chemical composition, the same as nearly all of the vessel glass from the site. The elevated Sb and Pb contents of this raw glass chip, 4311 ppm and 2844 ppm respectively show that it was recycled glass.

The five tesserae samples are in two colours, turquoise (three samples) and blue (two samples). From their major and minor chemical compositions, we can see that they are typical natron glass chemical compositions with high Na_2O, low K_2O and low MgO; the turquoise samples are coloured by copper and the blue samples are coloured by cobalt. Three of the five tesserae (Dor 145, 146, 147) have very high Sb contents of over 10000 ppm, a concentration significantly higher than that found in recycled Foy 2 glass. This compositional feature confirms that they are Roman glass with high Sb due to the presence of calcium antimonate opacifying crystals.

The opaque yellow glass rod (Dor 149) has a similar chemical composition to opaque yellow glass from Maastricht, Jodenstraat and Wijnaldum. It has high Na_2O and PbO contents and low K_2O and MgO contents: it is also coloured by lead tin yellow II. Therefore it would have been made using the same procedure as the opaque yellow glass from Jodenstraat and Wijnaldum: natron glass was used as the base glass, and it was coloured by lead tin yellow II. The Al_2O_3/SiO_2, TiO_2/Al_2O_3 ratios and low Sb content of Dor 149 suggest that the base glass used could also have been 'pristine' Foy 2 glass.

5.7 Glass samples from Susteren

The glass samples from Susteren fall into four categories: trail decorated glass beads (six samples), window glass (ten samples), glass attached to crucibles (two samples) and vessel glass (eleven samples).

5.7.1 Trail decorated glass beads

The trail decorated glass beads (Sust 1–6) do not occur on the other sites studied here. The bodies of the trail-decorated glass beads are mainly a green colour of different shades, and the decorated glass trails are red, yellow and white. The matrix glass of all six trail-decorated glass beads was analysed (Sust 1–6 body); five coloured glass trails were analysed too (Sust 2–6 trail). The chemical compositions of the bodies shows that four of them are made from natron glass and two (Sust 3 and 4) were made from plant ash glass. In the Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot, three natron glass bead bodies (Sust 1, Sust 2 and Sust 6) distribute in the area of the Foy 2 compositional group while the Sust 5 body composition locates in the area of Egyptian II glass compositional group (Figure 5.17a with Figure 4.1 as reference). The elevated copper, antimony, lead and tin contents of four body glass samples suggest they were made from recycled glass (Figure 5.17a).

There are two other glass samples from Susteren with compositional features like Sust 5: Sust 14 (window glass) and Sust 22 (glass vessel). They are recycled glass with high Sb and Pb contents over 1000 ppm, and they plot together in the area of the Egyptian II compositional group in the Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot. The chemical compositions of bead Sust 3 and Sust 4 bodies are clearly different from that of the other four trail-decorated bead bodies as they are soda-lime-silica glass with high K_2O and MgO contents and are therefore plant ash glasses. More details regarding the possible origins of these glass beads are given in Section 5.10.7.

As for the coloured glass trails, the red colour (Sust 2) contains high levels of CuO (1.74%) and Fe_2O_3 (4.59%) in a natron glass

[295] Gratuze *et al*. 2003; Pactat *et al*. 2017.

matrix. This suggests that the colour could be a result of 0 valence copper micron sized metallic particles and the iron inclusions, perhaps introduced in a slag, would have acted as an internal reducing agent.[296] The opaque yellow colour of Sust 3 trail decorated glass bead has a similar chemical composition to the yellow glass beads from Maastricht Jodenstraat and Wijnaldum: it is coloured with lead tin yellow II.[297]
The colouring mechanism of opaque white Sust 4 and Sust 6 is different from any other opaque white glass beads studied in this work as they are not coloured by tin-based opacifiers but by calcium antimonate crystals. This suggests the opaque white glass trails are recycled Roman opaque white tesserae. Opaque yellow Sust 5 is also different from other opaque yellow glass studied here: it is coloured by lead antimonite rather than lead tin yellow II. This also suggests that the yellow glass used for the trail may have been recycled Roman tesserae.[298]

5.7.2 Window glass

As for the window glass samples, apart from Sust 11, which is a wood ash glass, the remaining nine window glass samples are all natron glass. In the Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot of these natron window glass samples (Figure 5.17a with Figure 4.1 as reference), Sust 16, which contains a high Al_2O_3 content at 3.6%, does not plot in the area of any recognized natron glass compositional group, and Sust 14 plots in the area of the Egyptian II glass compositional group, while the remaining seven samples all distribute in the area of the Foy 2 compositional group. All natron window glass samples contain elevated Sb and Pb contents (Figure 5.17b), suggesting they are recycled rather than pristine glass. We also noticed that Sust 7 and Sust 8 contain extra high Sb_2O_3 contents (1.58% and 1.70% respectively), which are much higher than that found in common recycled Foy 2 glass. The wood ash glass Sust 11 has very high P_2O_5 (2.5%), MgO (5.6%), CaO (11.0%) and K_2O (14.2%) levels, which is a typical of northern European wood ash glass dating to the late 8th century at the earliest.

5.7.3 Glass attached to crucibles

The two glass samples attached to crucibles (Sust 17, Sust 18) are natron glass but their composition is different from common natron glass. Sust 17 contains high Sb_2O_3 (1.5%) and K_2O (5.2%) contents, but less than 1 wt% MgO. This peculiar composition may suggest the addition of recycled Roman tesserae and contamination from furnace wood ash. On the other hand, Sust 18 contains high Al_2O_3 (7.74%) and K_2O (3.3%), which suggests that the glass has been contaminated by interaction with the crucible fabric.[299]

5.7.4 Vessel glass

Eleven vessel glass samples from Susteren have been analysed. Their chemical compositions show that apart from two samples, Sust 19 (the pale green tubular base of a funnel beaker) and Sust 28 (a pale green funnel beaker fragment decorated with a green and white reticella rod), the others are natron glass. The Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios of the nine natron glass samples indicate that Sust 26 (a nearly colourless funnel

[296] Peake & Freestone 2012.
[297] Henderson 2023.
[298] Henderson 2023.
[299] Henderson 2023.

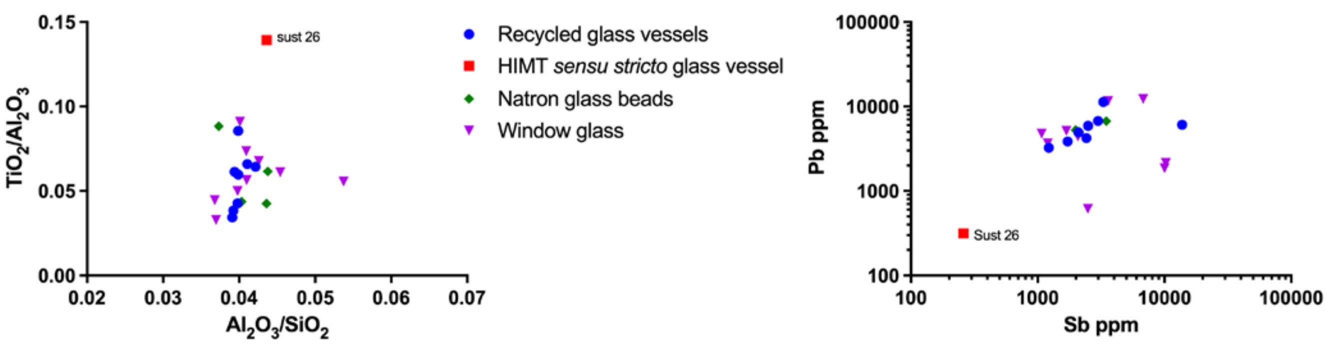


Figure 5.17 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Susteren natron glass samples.

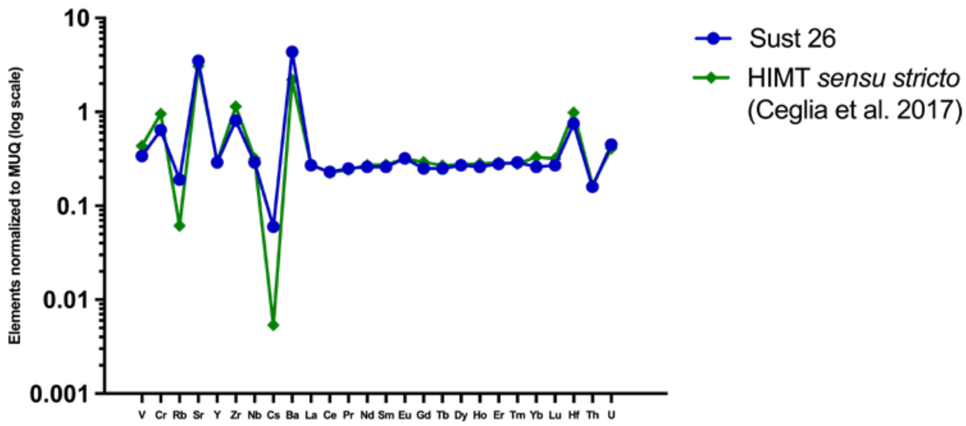


Figure 5.18 The 26 trace element pattern of Sust 26 compared to that of the relevant HIMT natron glass type.

beaker with a dark blue incalmo rim) belongs to the HIMT *sensu stricto* compositional group and Sust 22 (a blue-green funnel base) plots in the area of the Egyptian II compositional group, while the other seven samples are of a Foy 2 composition (Figure 5.17a with Figure 4.1 as reference). The Sb and Pb concentrations show that Sust 26 was made from ‘pristine’ glass while the other eight samples were made from recycled glass (Figure 5.17 right). The 26 trace element pattern of Sust 26 matches with that of pristine HIMT *sensu stricto* reported previously (Figure 5.18). Therefore this confirms that Sust 26 was made from ‘pristine’ HIMT *sensu stricto* glass.

Sust 19 is a highly weathered funnel base which contains Na_2O and K_2O at 8.87% and 8.5% respectively. It is therefore a mixed alkali glass. Sust 28 is a plant ash glass sample containing 0.3% P_2O_5, 4.2% MgO, 2.5% K_2O and 7.0% CaO. The trace element composition of Sust 28 has shed light on its provenance; this will be addressed along with other plant ash samples identified in this work in the discussion below.

5.8 Glass samples from Deventer

Forty one samples from Deventer-Stadhuis-kwartier were analysed. Apart from two monochrome glass beads (Dev 2, 8), the rest of the samples are glass vessels, window glass and raw glass fragments. Four compositional types of glass were identified. The largest number are wood ash glass (19 samples), thirteen samples are natron glass, four samples are mixed alkali glass and one sample is plant ash glass. Four samples were too weathered to be worthy of analysis (DEV 16, 17, 23, 34). Deventer samples are elaborated according to their compositional types in the following.

5.8.1 Wood ash glass

The 19 wood ash glass samples are all vessel and window glass. The sample numbers are: DEV 1,6,7,8, 14,15, 21, 24, 26, 27, 28, 29, 30a, 32, 33, 35, 36, 38 and 39. The main fluxing agent in wood ash glass is K_2O, with CaO in variable amounts. These wood ash glasses generally have high MgO contents over 3.5%, high P_2O_5 contents over 2.0% and low Na_2O contents of below 3.0%. Apart from sample Dev 24, which has a CaO/K_2O ratio of 5.8 which is the only example of a high lime (23.6% CaO), low alkali (2.9% Na_2O, 4.1% K_2O) glass (HLLA), the rest of the 19 samples have CaO/K_2O ratios from 0.7 to 2.0 with an average at 1.1. Deventer 24 is a pale blue-green window fragment: its chemical composition is much more typical of medieval and post-mediveal glass[300] so a later production date for it can not be ruled out (however see Section 6.5). The chemical compositions of early medieval wood ash glass are not especially well defined and as can be seen from previously published results they are quite variable.[301] Analytical research on later (13^{th} century) wood ash glasses provide some broad compositional trends but the origins in northern France, ‘Rhenish’ (based on borders of *c.* 1300 AD which includes the Low Countries) and central Europe

300 Van Wersch *et al.* 2018.
301 Wedepohl & Simon 2010.

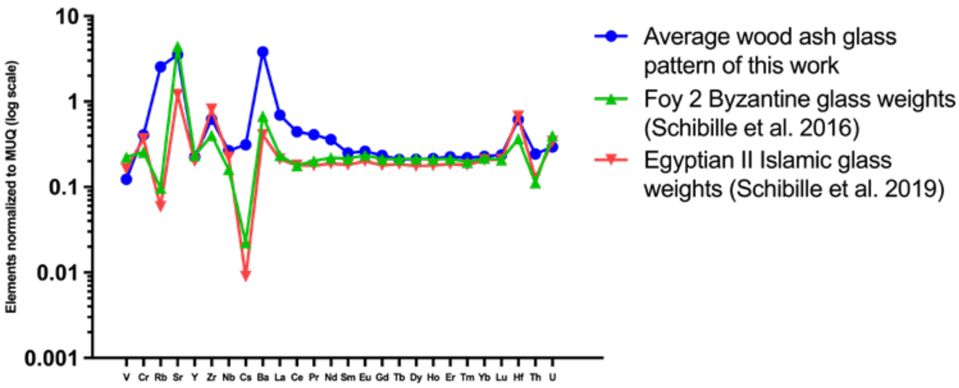


Figure 5.19 The average 26 trace element patterns of wood ash glass samples from Deventer compared to that of relevant natron glass studies published previously.

do not provide especially clear distinctions and in many cases the 'types' overlap.[302] Moreover a comparison with earlier Deventer wood ash glasses offers a somewhat confused picture and such a comparison is, in any case, inappropriate given the difference in dates associated with the different socio-economic contexts of production. The 26 trace element pattern of the average composition of these wood ash glass is plotted in Figure 5.19 along with that of natron glasses of selected compositional groups (Foy 2 and Egyptian II) reported previously. We can see that the trace element pattern of wood ash glass is quite different from that of natron glass, especially the clearly elevated Rb, Cs and Ba contents.

5.8.2 Natron glass

Among the thirteen natron glass samples (DEV 2, 3, 9, 10, 11, 12, 13, 19, 20, 25, 31, 40, 41), three samples, surprisingly for such a late site, have features suggesting that they are of a Roman provenance: Dev 9 (an amber coloured fragment), Dev 13 (a funnel beaker with a very high Mn content suggesting Mn decolourisation) and Dev 20 (a typical Roman vessel shape, Isings 96a). All date to between 900 and 950 AD. At the same time, the three samples also distribute in the Roman glass area in the Al_2O_3/SiO_2 against TiO_2/Al_2O_3 plot and have low Sb and Pb concentrations <1000 ppm (Figure 5.20). Therefore they can definitely be identified as glass produced in the Roman tradition.

The Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios of the other ten natron glass samples show that Dev 11 (the rim of a possible funnel beaker), Dev 31 (possible window glass) and Dev 40 (a fragment of dark and light green layered glass) all plot in the area of Egyptian II glass; they date to 900–925, 890–925 and 950–1050 AD respectively according to the find contexts. The rest belong to the Foy 2 compositional group (Figure 5.20a with Figure 4.1 as reference) and date to between 850 and 1050. The Sb and Pb concentrations of the ten samples suggest that

[302] Adlington *et al.* 2019.

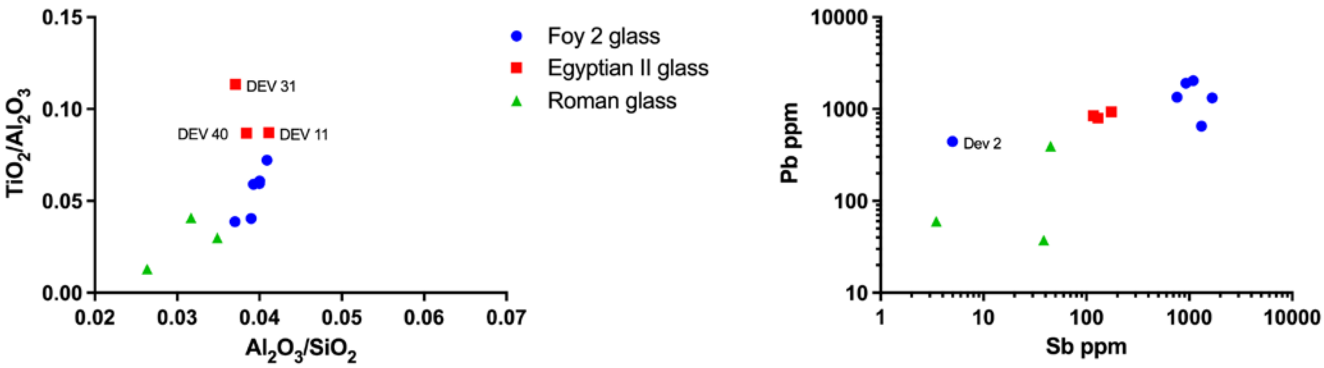


Figure 5.20 Plots of Al_2O_3/SiO_2 against TiO_2/Al_2O_3 (a) and Sb against Pb (b) for Deventer natron glass samples.

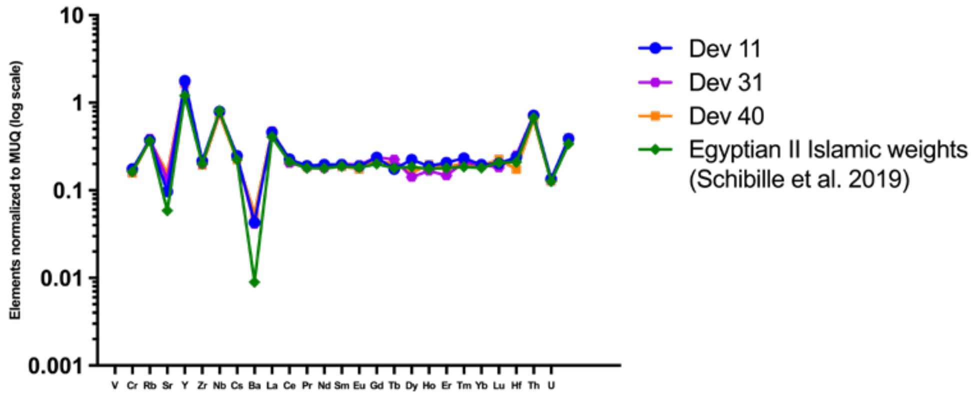


Figure 5.21 The 26 trace element patterns for Deventer 11, 31 and 40 compared to that for relevant Egyptian II natron glass published previously.

the Egyptian II subgroup (Dev 11, Dev 31 and Dev 40) are all 'pristine' glass while only one Foy 2 monochrome blue glass bead (Dev 2) is a 'pristine' glass (Figure 5.20b) dating to 850–900 AD. The 26 trace element pattern of Dev 2 confirms that it was made from 'pristine' Foy 2 glass, while the patterns for Dev 11, Dev 31 and Dev 40 confirm that they were made from 'pristine' Egyptian II glass (Figure 5.21). The rest of the Foy 2 glasses are recycled.

5.8.3 Mixed alkali glass

The four mixed alkali glass samples from Deventer (DEV 4, 5, 18, 22) are an interesting group, which are not found amongst glasses reported elsewhere in this study and are a reflection of their production date. The samples tested derive from archaeological contexts dated to between 850 and 950 AD. Their high MgO contents (>1.8%) suggest the potassium content was introduced in the form of plant ash/wood ash rather than potassium-containing minerals. Their Na_2O/K_2O values are variable, between 0.5 and 1.7. Glass with similar features has also been found in 8^{th}–10^{th} century sites in Germany, France and the Netherlands (see Section 2.4.1). It has been suggested that this type of mixed alkali glass was produced in order to extend stocks of soda glass,[303] and the procedure can be interpreted either as the mixing together of wood ash and natron glasses or, less likely, by the addition of an increasing amount of wood ash in a mixture of glass cullet.[304]

Two mixed alkali glasses have elevated PbO contents of between 2.4 and 2.8% lead oxide. This could be interpreted as an addition of lead glass, introduced during the recycling process and which should not be regarded as a surprise if a 'potluck glass working' strategy was used during glass recycling.

5.8.4 Plant ash glass

The one plant ash glass identified from the Deventer assemblage (Dev 37) is a green possible beaker fragment with a little weathering, from a context dating to between 950 and 1050. It has a typical plant ash chemical composition. It is a soda-lime-silica glass with high MgO and K_2O contents at 1.8% and 4.77% respectively. Discussion of its possible origin is given in Section 5.10.7.

In contexts dating to 850-900 AD, six out of eight samples are wood ash or mixed alkali glasses, with the remaining two being recycled Foy 2. In contexts dating to between 900 and 950 AD there are ten wood ash glasses, three Roman (natron) glasses, two recycled Foy 2 glasses and two Egyptian II glasses. Two glasses dating to between 950 and 1000 are wood ash; between 950 and 1050 four glasses are of the wood ash type, one is plant ash, one recycled Foy 2 and one Egyptian II. Given that there is no evidence for a wood ash glass industry in the Netherlands possible ways that wood ash glass was imported, would have been as part of the Viking trade network or from the various sites further north.

303 Krueger & Wedepohl 2003.
304 Pactat *et al.* 2017.

5.9 Nd-Sr isotope analysis

Twenty samples selected from Maastricht (Jodenstraat), Wijnaldum and Dorestad were analysed for their strontium and neodymium isotopic compositions, and eighteen valid results were obtained. In this study $^{143}Nd/^{144}Nd$ ratios are represented in parts per 10^4 deviation from the present-day value of a model evolution of Nd isotopes in a chondritic Earth (Chondritic Uniform Reservoir, CHUR)[305] according to the following equation:

$$\varepsilon Nd = \left(\frac{(^{143}Nd/^{144}Nd)_{Sample}}{(^{143}Nd/^{144}Nd)_{CHUR}} - 1\right) \times 10^4, \text{ with } ^{143}Nd/^{144}Nd_{CHUR} = 0.512638$$

The strontium and neodymium isotopic compositions of our 18 samples and their chemical compositional groups are listed in Table 5.3 and plotted in Figure 5.22. The two wood ash glass samples, Dor 136 and Dor 150, both lead-rich linen smoothers, have very different Nd–Sr isotopic signatures from the other samples. Their Nd isotopic signatures reflect the Nd isotopic signatures of the sands used for making them, and their Sr isotopic signatures reflect the bio-available Sr isotopic signatures in the calcium-rich raw materials used to make them. The Sr from wood ash glass would have mostly been introduced in the wood ash used as the flux. The Nd–Sr isotopic signatures of Dor 136 and Dor 150 have a similar range to that of 14th–15th century forest glass produced in Staffordshire, England.[306] However there are no other Nd–Sr isotopic datasets of wood ash glasses by geographic region currently available so we cannot suggest provenances based on Nd–Sr results for two wood ash glass samples at this stage.

The only plant ash sample, WIJ 37, from the assemblage clusters together with natron glass samples in figure 5.22 but it has a low $^{87}Sr/^{86}Sr$ signature. Comparing the Nd–Sr isotopic signatures of WIJ 37, a silver foil colourless bead, with that of other available plant ash glass data (Figure 5.23), we found that it overlaps with 3rd–7th century Sasanian glass found in Veh Ardašīr, an old Sasanian administrative centre 40 km to the southeast of modern Baghdad.[307] Although the 3rd–7th century Sasanian glass samples from Veh

Table 5.3 The Nd–Sr isotopic compositions and compositional groups of samples analysed (WIJ=Wijnaldum; DO=Dorestad).

Sample number	Compositional group	$^{143}Nd/^{144}Nd$	εNd	$^{87}Sr/^{86}Sr$
Maastricht-Jodenstraat 47	'pristine' Foy 2	0.512	-5.6	0.709
Maastricht-Jodenstraat 49	'pristine' Foy 2	0.512	-7.6	0.709
Maastricht-Jodenstraat 58	'pristine' Foy 2	0.512	-5.4	0.709
Maastricht-Jodenstraat 63	'pristine' Foy 2	0.512	-5.4	0.709
Maastricht-Jodenstraat 68	Roman glass	0.512	-5.2	0.709
Maastricht-Jodenstraat 73	'pristine' Foy 2	0.512	-6	0.709
Maastricht-Jodenstraat 76	'pristine' Foy 2	0.512	-5.6	0.709
WIJ 13	recycled Foy 2	0.512	-5	0.709
WIJ 27	not identified	0.512	-6.8	0.709
WIJ 36	'pristine' Foy 2	0.512	-5.4	0.709
WIJ 37	plant ash glass	0.512	-6.4	0.709
DOR 111	recycled Foy 2	0.512	-6	0.709
DOR 113	recycled Foy 2	0.512	-5.6	0.709
DOR 115	recycled Foy 2	0.512	-6	0.709
DOR 128	recycled Foy 2	0.512	-5	0.709
DOR 136	wood ash glass	0.512	-9.9	0.715
DOR 147	Roman tesserae	0.512	-6.2	0.709
DOR 150	wood ash glass	0.512	-10.7	0.711

305 Depaolo & Wasserburg 1976.
306 Meek, Henderson & Evans 2012.
307 Ganio *et al.* 2013.

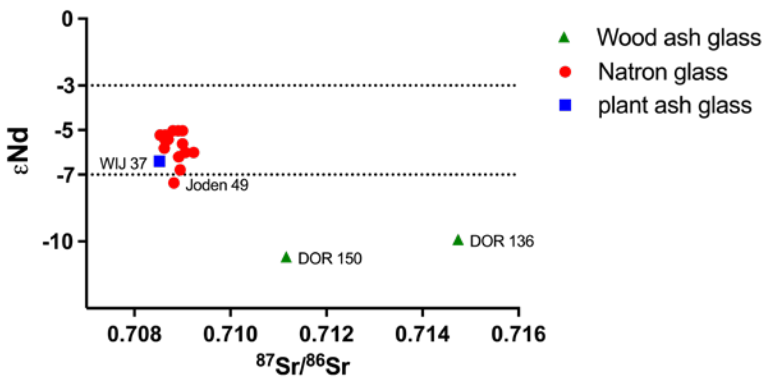


Figure 5.22 A Nd–Sr isotopic plot of the glasses analysed; WIJ 37, Joden 49, DOR 136 and DOR 150 are labelled separately (WIJ= Wijnaldum; DOR = Dorestad; Joden = Jodenstraat, Maastricht).

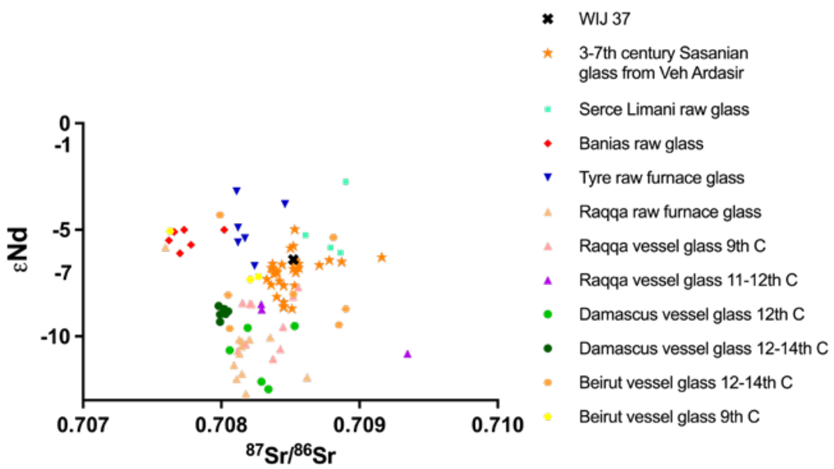


Figure 5.23 A Nd–Sr isotopic plot of WIJ 37 compared with that of plant ash glasses from the Middle East published previously (WIJ = Wijnaldum). Data source: 3rd–7th century Sasanian glass Nd–Sr isotopic data is from Ganio *et al.* (2013), Tyre raw furnace glass from Degryse *et al.* (2010), al-Raqqa 9th century and 11th–12th century vessel glass data from Henderson, Evans & Barkoudah (2009), the rest from Henderson, Ma & Evans (2020).

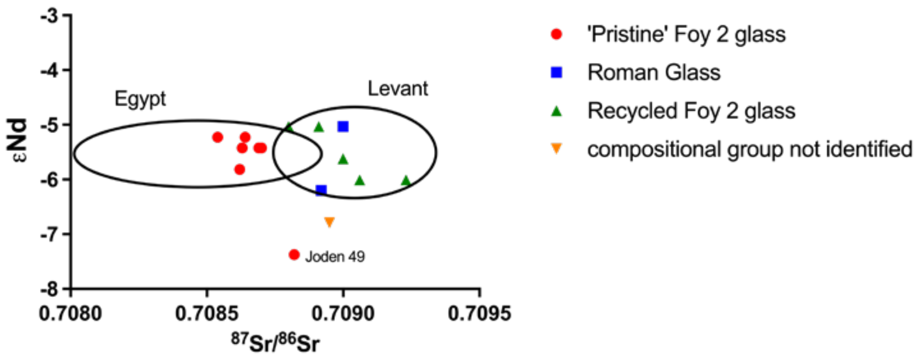


Figure 5.24 A Nd–Sr isotopic plot of the natron glass samples analysed. Joden 49 is labelled separately (Joden = Jodenstraat, Maastricht). The ellipses are drawn according to Degryse & Schneider (2008).

Ardašīr are too early for the late 9th century date of WIJ 37, this observation still sheds some light on the possible geographical origin of this plant ash glass sample. This is addressed in detail along with other plant ash samples identified in this study in Section 5.10.7.

We have suggested that Joden 68 was a Roman ribbed vessel fragment: this is confirmed as a Roman natron glass from its major and minor chemical elemental composition; Dor 147 is a

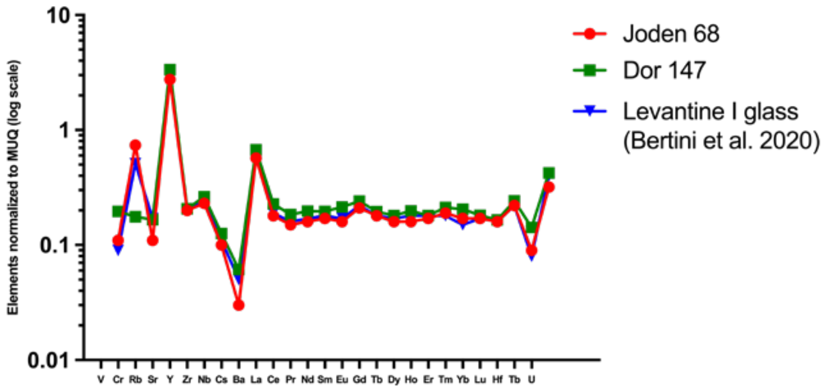


Figure 5.25 The 26 trace element patterns for Joden 68 and Dor 147 compared to that for Levantine I natron glass published previously (Joden= Jodenstraat, Maastricht; DOR = Dorestad).

Roman glass tessera. We did not try to make further provenance identification based on their trace element data since the geographical production centre of this Roman glass type is not yet clear. Joden 68 has a $^{87}Sr/^{86}Sr$ of 0.7090 and εNd of -5.03, and Dor 147 has a $^{87}Sr/^{86}Sr$ of 0.70892 and εNd of -6.20, typical Nd–Sr signatures of glass produced in Levant.[308] Following this lead, we compared the trace element patterns of Joden 68 and Dor 147 with that of early medieval Levantine glass, and we found they both have similar trace element patterns to Levantine I glass (Figure 5.25). This observation indicates that Joden 68 and Dor 147 were made with a similar sand source as that used for making Levantine I glass. Therefore we suggest that Joden 68 and Dor 147 are Roman glasses produced in the Levant.

The Nd–Sr isotopic compositions of the thirteen natron glass samples mostly distribute in the typical range for natron glass Nd–Sr signatures, εNd at between -5 and -7, and $^{87}Sr/^{86}Sr$ at between 0.7085 and 0.7093,[309] except for one outlier: Joden 49, a drop of green glass with soil contamination (Figure 5.24). The εNd of Joden 49 is -7.3, lower than the normal range of natron glass $-7 \leq$ εNd ≤ -3, and this may be related to contamination. Twelve out of the thirteen natron samples have been identified as belonging to the Foy 2 compositional group: seven 'pristine' Foy 2 glass and five recycled Foy 2 glass (Table 5.3), and the $^{87}Sr/^{86}Sr$ ratios of the twelve samples stretch in a rather wide range between 0.7085 and 0.7093. Six out of the seven 'pristine' Foy 2 glasses (except for the outlier Joden 49) actually cluster closely at $^{87}Sr/^{86}Sr$ of 0.7086, a typical value for glass produced in Egypt, the commonly suggested origin of Foy 2 glass. Five of these samples are the working debris from bead production in Maastricht (a glass strand, a drop and three rods) and a gold foil bead from Wijnaldum.

The $^{87}Sr/^{86}Sr$ values for five recycled Foy 2 glass samples, a pale green funnel beaker from Wijnaldum as well as two funnel beakers, one palm funnel and a gold leaf decorated funnel from Dorestad stretch between 0.7088 and 0.7093. This is higher than the typical Egyptian range. These recycled 'Foy 2' glasses are all dated to the late 8th to mid-9th century.
We suspect the Sr isotopic signatures of recycled Foy 2 glass samples would have changed from the 'pristine' Foy 2 values during the recycling process, which would have involved mixing different types of glass. The mixing of glass types with very high $^{87}Sr/^{86}Sr$ values (such as wood ash glass), into a mainly natron glass recycling batch, would have caused the elevation of $^{87}Sr/^{86}Sr$ values in the recycled natron glass compared to 'pristine' natron glass. Evidence of recycling/mixing wood ash glass along with natron glass has also been noted in the trace element patterns of recycled Foy 2 glass dated to the late 8th century and later. This is addressed in Section 5.10.4.

[308] Degryse & Schneider 2008.
[309] Brems *et al.* 2018.

5.10 Discussion

5.10.1 The base glass used for bead making at Jodenstraat

It has been suggested that a two-step procedure was used for the manufacture of highly coloured opaque glass beads in early medieval northwestern Europe: first, naturally coloured or colourless base glass was coloured and made into rods or strands. Then coloured glass rods or strands were softened and formed into beads.[310] Apart from the highly coloured opaque glass objects, the site of Jodenstraat in Maastricht also yielded translucent naturally coloured and cobalt blue bead-making waste, which is ideal to test this two-step production proposition and understand what kind of glass was used as the base glass.

In this work we found three types of evidence that prove that the naturally coloured translucent glass-working debris is of the same compositional type as the base glass used to make opaque glass and thus that the two-step production proposition stands. Firstly, the Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios of the coloured opaque glass-working remains and translucent glass samples cluster together and they can all be categorized as being of the Foy 2 type. From the Al_2O_3/SiO_2 versus TiO_2/Al_2O_3 plot we can see that, on average, highly coloured glasses have a slightly higher Al_2O_3/SiO_2 ratio than naturally coloured glass debris: the cluster of highly coloured glasses plot slightly to the right of the cluster of naturally coloured glass-working debris (Figure 5.1). This can be attributed to the higher Al_2O_3/SiO_2 ratios of the lead tin yellow colourant and tin opacifiers that were added to the highly coloured glass matrix (Table 5.1).

Secondly, the Sb contents of the naturally coloured glass-working debris and highly coloured glass samples are all very low, suggesting they were both made from 'pristine' glass. Finally, the 26 trace element patterns of the average composition of the naturally coloured bead-making artefacts and the average composition of the highly coloured glass are identical and the same as that of 'pristine' Foy 2 glass previously published. Therefore we can suggest strongly that the naturally coloured bead-making artefacts found at the Maastricht Jodenstraat site were made from the same glass as the base glass used for making the opaque glass beads: it is all 'pristine' Foy 2 glass.

5.10.2 The use of crucibles in on-site lead tin yellow colourant production in early medieval northwestern Europe

Early medieval lead tin yellow residues attached to crucibles from northwest European sites have been studied before.[311] The shapes of the crucibles containing lead tin yellow residues are mostly shallow and with a wide opening that resembles a tray. It has been suggested this type of crucible was not used for metallurgical processes but was specifically used for making the lead tin colourant for yellow coloured beads,[312] which were very popular in early medieval Europe. We agree with the suggestion that the crucibles with yellow residues were used for making the yellow colourant for bead making, since the main phase in the yellow residue is lead tin yellow II ($PbSn(Si)O_3$), the common colouring agent of yellow beads at the time. However, from the study of the rich material remains related to bead making found at Jodenstraat Maastricht, we have managed to provide some new insights into how lead tin yellow was made in these tray shaped crucibles.

It has been suggested that this type of crucible may have been used for calcining lead and tin, a chemical reaction which would result in lead tin yellow I, and that lead tin yellow II identified in the crucible may have been formed by the reaction between the siliceous crucible body and lead tin yellow I.[313] Heck and colleagues also suggested that the colourant produced in the crucible was to be mixed, in a ratio of one to one by volume, with natron glass to make the yellow glass for beads.[314] Peake and Freestone[315] studied yellow beads from Tarbat Ness and Eriswell and reviewed the results of Henderson and Ivens[316] and Heck and colleagues[317] for the yellow residues attached to crucibles, and concluded that the reaction which occurred in the crucible, resulting in the lead tin yellow II colourant, involved silica as a raw material.

The thorough replication experiments to produce lead tin yellow colourant by Rooksby[318] and Matin and colleagues[319] demonstrated that the

310 Sablerolles, Henderson & Dijkman 1997.
311 Henderson & Ivens 1992; Heck, Rehren & Hoffmann 2003; Peake & Freestone 2014.
312 Heck, Rehren & Hoffmann 2003.
313 Heck, Rehren & Hoffmann 2003.
314 Heck, Rehren & Hoffmann 2003.
315 Peake & Freestone 2014.
316 Henderson & Ivens 1992.
317 Heck, Rehren & Hoffmann 2003.
318 Rooksby 1964.
319 Matin, Tite & Watson 2018.

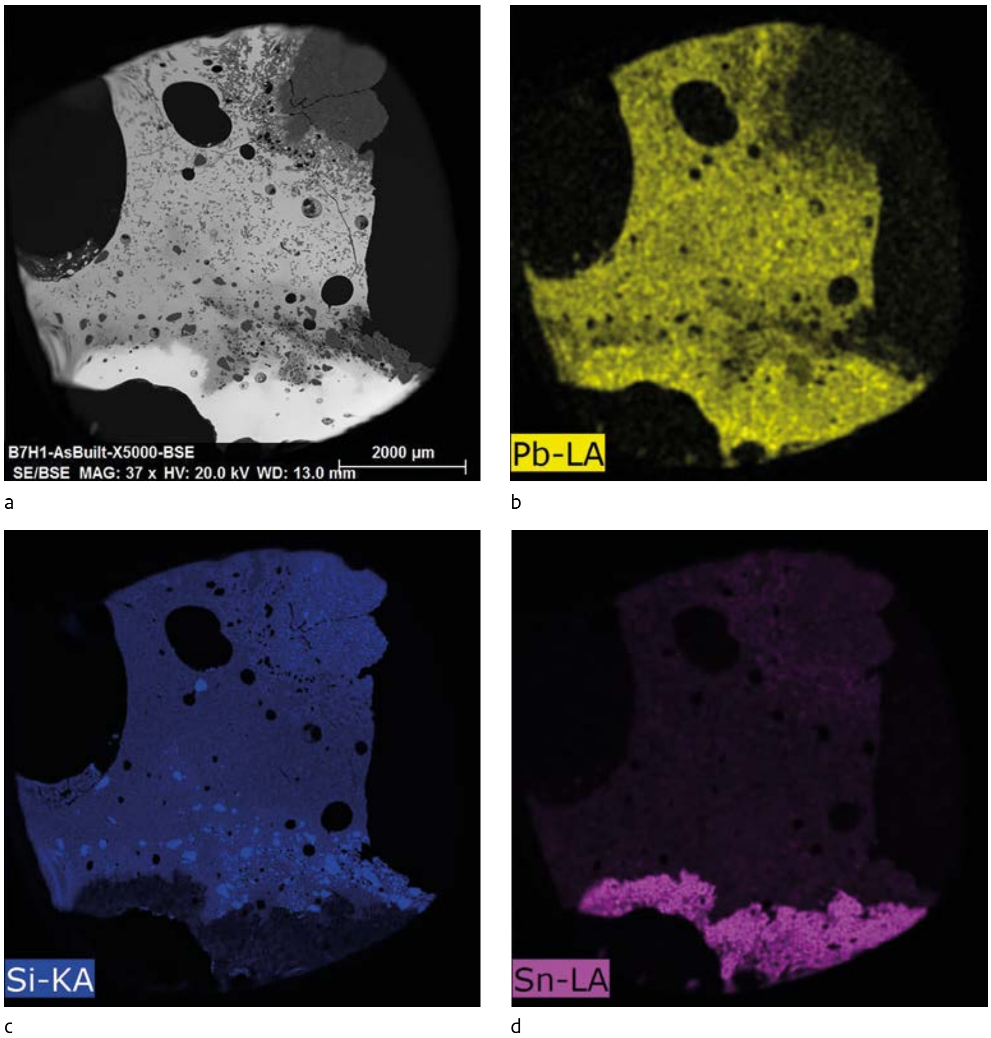


Figure 5.26 Backscattered SEM image (top left: 5.26a) for Joden 19 showing the unmelted silica grains. Elemental lead maps for Joden 19 lead (Pb) (top right: 5.26b), silica (Si) (bottom left: 5.26c) and tin (Sn) (bottom right: 5.26d) (Joden = Jodenstraat, Maastricht).

yellow colourant for glass- and glaze-making would have been produced in a two-step procedure, as recorded in ancient Islamic literature. Firstly, a lead tin calx, which contains lead tin yellow I ($PbSn_2O_4$) as the main component, is produced by calcining lead and tin together in a stoichiometric ratio of Pb:Sn over 3.5. Then lead tin calx is mixed with silica and the mixture is heated to over 800°C for the lead tin yellow colourant (lead tin yellow II) used in glass- and glaze-making to be produced. During the second step, variable amounts of SiO_2 substitute for SnO_2 in $PbSn_2O_4$ (lead tin yellow I) which causes a crystalline conversion to $PbSn(Si)O_3$ (lead tin yellow II).

No lead tin yellow I phase has been identified in the yellow tin residues in this study, and the chemical composition of lead tin yellow II attached to crucibles is in good agreement with that found in the yellow glass and yellow beads, especially with respect to the Sn to Si ratio, which could be variable depending on how much Sn was replaced by Si during the reaction involving lead tin yellow I and silica. Therefore we suggest that the lead tin yellow colourant production procedure used by early medieval northwestern European bead makers would have been very similar to that recorded in later Islamic literature. This was a two-step procedure: the tray shape crucibles with lead tin yellow residues attached would have been used during the second step when heating silica with lead tin yellow I for making lead tin yellow II occurred.

Silica grains are observed in one of our samples (Joden 19) in support of this suggestion (Figure 5.26), also observed in the Early Christian Irish evidence from Dunmisk.[320]

5.10.3 The separate production of a tin-based white opacifier at Maastricht, Jodenstraat

Apart from crucibles containing lead tin yellow residues, two crucibles containing tin white residues (Joden 23 and Joden 30) were found at Jodenstraat. Our study shows that the main phase of the white residues is SnO_2 (50–70 wt%) in the presence of variable amounts of PbO and SiO_2 (see Section 5.2.3). Because the Sn:Pb ratio in the tin white residues is very different from that of lead tin yellow residues and very similar to the tin-based opacifiers found in the white, red and greenish-blue glass and beads, we can strongly suggest that the tin-based opacifiers were intentionally produced as a separate material on site at Jodenstraat and that they were probably used directly in the production of the white, red and greenish-blue glass for bead making.

Highly coloured glass opacified by tin-based opacifiers re-emerged around the same time when lead tin yellow glass became mainstream in northwest Europe in *c.* 3rd century AD.[321] Although early medieval northwestern European lead tin yellow colourant production has been studied on a few occasions, the two crucibles containing tin-based opacifiers used to make white glass are the first reported evidence confirmed by scientific analysis that tin opacified white glass was produced separately in early medieval northwestern Europe.

In a previous study of bead-making materials from Jodenstraat[322] it was suggested that the white, red and greenish-blue glass rods found at the site for producing beads of the same colours may have been imported from other sources since no crucibles containing glassy residues of these three colours were found at the site. Two extra pieces of evidence identified here suggest that the white, red and greenish-blue glass rods for producing beads of the same colours were also produced on site, rather than being imported from elsewhere. Firstly the base glass of all four different coloured glasses and beads as well as the colourless glass from working the glass were made from a very similar 'pristine' Foy 2 glass (see Section 5.10.1), and secondly the opacifiers used in the white, red and greenish-blue glass were probably also produced on site.

The contrasting PbO contents (Figure 5.3) between yellow glass and the white, red and greenish-blue glasses is probably also related to the use of lead tin yellow colourant in the yellow glass and tin-based opacifiers in white, red and greenish-blue glass. When the lead tin yellow colourant was produced, a pure lead silica glass formed around lead tin yellow II in the lead tin yellow colourant as we can see in Figure 5.5. When in the third stage the colourant is added to the melted natron base glass, the pure lead silica glass would have melted and mixed into it and the lead content of the resulting glass would have increased greatly as a result.

On the other hand, the production of the tin-based white opacifier would have involved far less lead; no pure lead silica glass formed around the tin opacifier.[323] So when the tin opacifier was mixed into melted natron base glass, lower levels of lead would have been introduced. This is a reasonable explanation for the source of the lead content in highly coloured opaque glasses and beads, and why there is a big difference in the PbO contents between yellow glass and glass of the other three colours (Figure 5.3). Moreover, the methods used to make the lead tin yellow colourant and tin oxide opacifier were different.

As we can see in the SEM backscattered images of the four highly coloured opaque glasses (Figure 5.4), the bright phase in yellow glass (lead tin yellow II crystals) consists of very small particles of a similar size and they are distributed homogeneously in the glass matrix, while the tin oxide crystals in white, red and green glass have heterogeneous crystal sizes and a lot of them are in rather big aggregates. This observation suggests that the lead tin yellow colourant (lead tin yellow II) may have been mixed with the base glass while they were both in melted or semi-melted state, and that is why the lead tin yellow II consists of small particles that are distributed homogeneously in the glass matrix. On the other hand, the white tin oxide opacifier may have been added in a powdered state after it was produced on site in a large volume.

[320] Henderson & Ivens 1992.
[321] Matin 2019.
[322] Sablerolles, Henderson & Dijkman 1997.
[323] Matin 2019.

5.10.4 The other chemical characteristics of the glass and its archaeological implications

Glass fragments from non-industrial contexts account for the majority of the samples studied. They include glass vessels, window glass and some raw glass fragments. Altogether 160 of such glass samples have been chemically analysed – 28 from Gennep, five from Jodenstraat Maastricht, nine from Wijnaldum, three from Utrecht, 56 from Dorestad, 21 from Susteren and 38 from Deventer. The majority (95) of these samples have been identified as recycled Foy 2 glass, corresponding to the Foy 2.2 group of Foy *et al*.[324] Nine HIMT *sensu stricto* glasses have been identified from the collection, and seven of them are from the site with the earliest date: Gennep (late 4th to mid-6th century). Eight 'pristine' Foy 2 glasses have been identified: they are from Gennep (six samples) and Maastricht Jodenstraat (two samples). They date to between the late 4th and early 7th centuries.

Six 'pristine' Egyptian II glasses have been identified: two from Wijnaldum, one from Dorestad and three from Deventer. Their dates provided by the archaeological contexts in which they were found are as follows: three date to 8th–9th centuries AD, two date to the early 10th century and one dates to between 950 and 1050 AD. They are consistent with or slightly later than the suggested date when Egyptian II glass was widely circulated, in the 8th and 9th centuries AD. Twenty seven wood ash/mixed alkali glass samples have been identified. They are from three sites: Dorestad (two samples), Susteren (two samples) and Deventer (24 samples) and their context dates are consistent with the suggested date when wood ash glass started to be made and was circulating in Europe from the late 8th century onwards.

Five Roman glasses have been identified: they are from Jodenstraat (Joden 68), Utrecht (Utr 79) and Deventer (Dev 9, 13, 20). Four plant ash samples have been identified: Sust 3, 4 and 28, and Dev 37. The remaining eight samples are five compositional outliers (Utr 78, Dor 95, Sust 14, 16, 22) and three highly weathered samples (Dev 16, 17, 23). We can see that the identified compositional types of these mainly vessel and window glass fragments are consistent with our current understanding of the dates when the different types of glass emerged, peaked and disappeared.

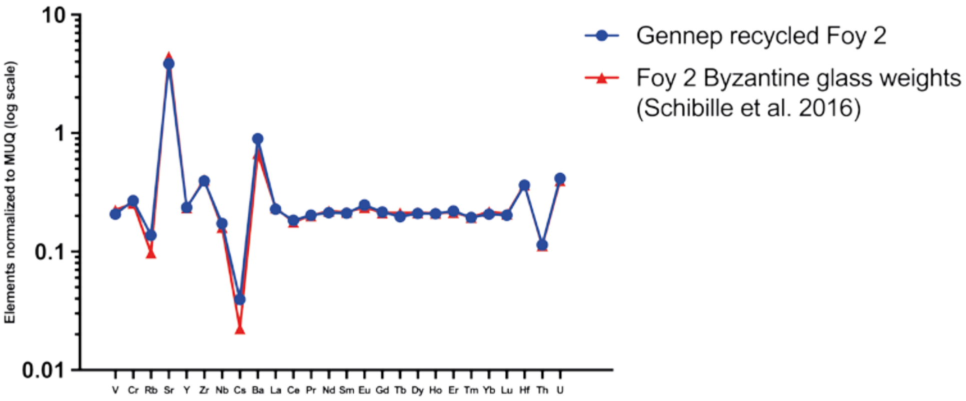
It has been concluded that HIMT glass in the widest sense (including HIMT *sensu stricto*, Foy 2 etc.) was in use from the middle of the fourth century until the seventh century.[325] However, in this study we have found that glass made from recycled glass with Foy 2 glass compositional features (referred to as recycled Foy 2 glass in this study, corresponding to Foy 2.2 group)[326] was still the dominant group between early 8th century and late 9th century (in Dorestad and Wijnaldum vessel glasses). It remained in circulation till possibly as late as the first half of the 10th century: four out of 38 glasses analysed from Deventer dated to 850–950 AD have been identified as recycled Foy 2 glass- with a single example, perhaps redeposited, in a context dating to 950-1000.

This means that recycled glass with Foy 2 compositional features was still in use centuries after the 'pristine' Foy 2 glass supply ended in northwestern Europe. The chemical composition of recycled Foy 2 glass samples, have some differences from that of 'pristine' Foy 2 glass, one of which is that they nearly all contain elevated Sb and Pb contents. This recycled version of Foy 2 glass (especially for Foy 2.1 subgroup) is labelled as Foy 2.2 subgroup in the work of Foy and colleagues,[327] and is known from a very limited number of assemblages in France, Italy and Spain that are typically dated to the end of the seventh and the eighth centuries AD.[328]

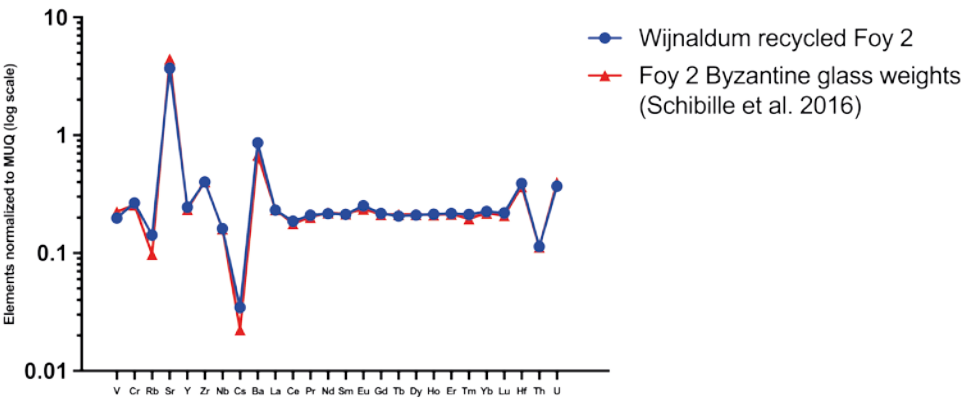
The 7th–11th century glass assemblage from Comacchio, northern Italy, is compositionally very similar to the samples studied here, as recycled glass with Foy 2 compositional features account for the majority of the glasses: the authors of that paper labelled such recycled glass 'intermediate'.[329] This observation is in line with the suggestion that around the early 8th century, Roman tesserae became a 'new' glass source in northwestern Europe; it was recycled along with other glass, supplementing the dwindling natron glass supply.[330] From the 26 trace element patterns of the average compositions of recycled Foy 2 glasses from Gennep, Wijnaldum, Dorestad, Susteren and Deventer we can see that they all retain the basic signature of 'pristine' Foy 2 glass (Figure 5.27).

However, we have also noticed that the 26 trace element patterns of recycled Foy 2

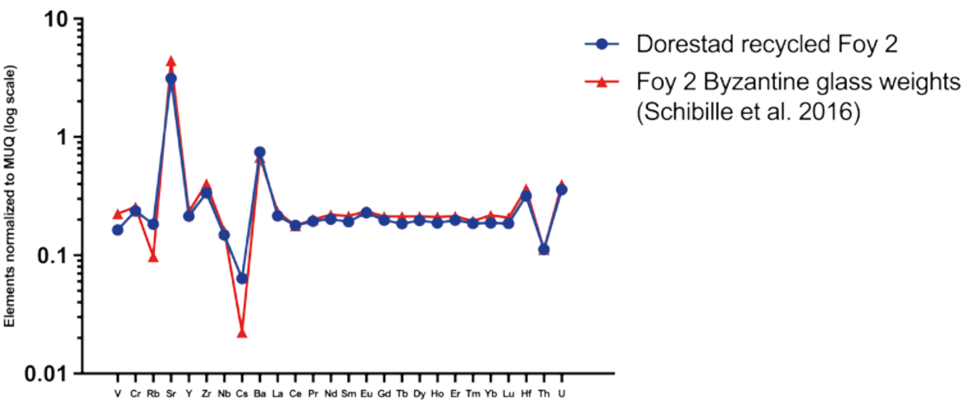
324 Foy *et al.* 2003.
325 Freestone *et al.* 2018.
326 Foy *et al.* 2003.
327 Foy *et al.* 2003.
328 Ares *et al.* 2019.
329 Bertini, Henderson & Chenery 2020.
330 Freestone 2015.



a

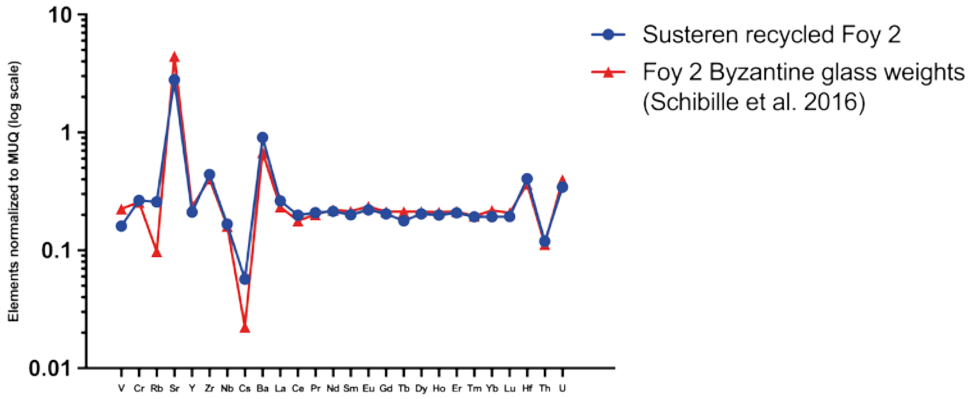


b

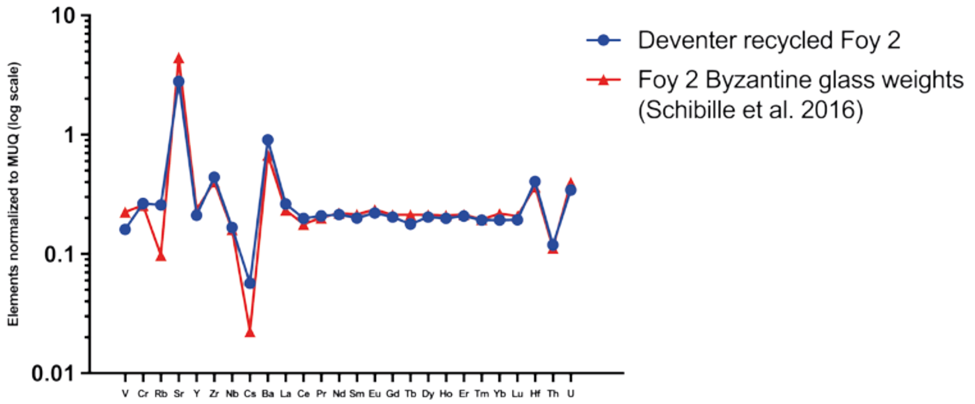


c

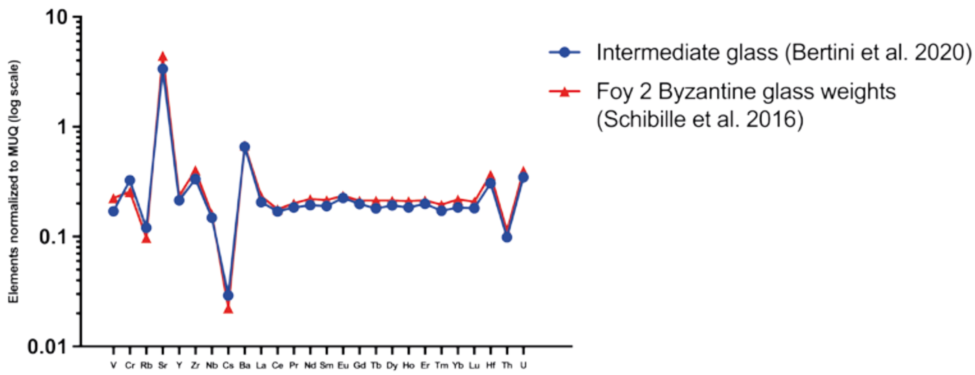
Figure 5.27 The average 26 trace element patterns of recycled Foy 2 glasses from Gennep (5.27a), Wijnaldum (5.27b), Wijk bij Duurstede (Dorestad) (5.27c).



d



e



f

Figure 5.27 (continued) The average 26 trace element patterns of recycled Foy 2 glasses from Susteren (5.27d), Deventer (5.27e) and 'intermediate' glass from Bertini, Henderson & Chenery (2020) (5.27f).

glasses from sites of the Carolingian period (Dorestad, Susteren) and slightly later at Deventer clearly have elevated Cs and Rb contents. Recycled Foy 2 glass from Gennep and Wijnaldum, which mostly predate the 8th century, do not show these features so strongly, nor do the recycled 'intermediate' group studied by Bertini and colleagues.[331] This could suggest that glass of a new compositional type started to be involved in glass recycling as a minor component in the Netherlands from around the start of the Carolingian period.

We suspect that this 'new' glass could have been wood ash glass since elevated Ba, Rb and Cs contents are the clear discriminating characteristics between wood ash and natron glass as defined by 26 trace element patterns with higher concentrations in wood ash glasses (Figure 5.19). This suggestion is also supported by the elevated Sr isotopic compositions of recycled Foy 2 glass samples dated to late 8th to mid-9th century from Wijnaldum and Dorestad, and in line with the understanding that wood ash glass started to be manufactured in Europe from the late 8th century in northwestern Europe. A further compositional characteristic of both Merovingian glass from Gennep and Carolingian glass from Dorestad is that potassium is correlated with both Rb and Li. An intriguing characteristic of these correlations (not shown here) is that Rb levels in the Gennep 'pristine' Foy 2 glass are mainly below 12ppm whereas the concentrations in Dorestad recycled Foy 2 glasses are mainly between 12ppm and 20ppm with a small number containing levels upto 28ppm. This is another clear marker of the increased degree of recycling in the later (Carolingian) glasses and the same thing is true for Li concentrations. Some Dorestad glasses contain between 23 and 40ppm Li. These same correlations found in 7th century and later Foy 2.1 glasses have been attributed to evidence of site-specific contamination from e.g. muscovite in the crucibles used for working the glass at Tolmo de Minateda, Spain. [332] Our results suggest that such contaminants including very similar concentrations of Rb and Li as in the Tolmo glasses may not be characteristic of local production in our case. A more likely interpretation is that the increase in concentrations of potassium, rubidium, lithium and cesium in Carolingian glasses compared to earlier glasses may be attributable to muscovites associated with sands used to make some of the glasses that were mixed as part of the Carolingian recycling processes involving Foy 2 glass.

5.10.5 A comparison of 7th–11th century vessel glass from Comacchio with early medieval Dutch glass and the suggested supply of raw glass in the two areas

We have mentioned that the recycled Foy 2 glass in this study bears similar compositional features to the 'intermediate glass' identified by Bertini and colleagues[333]; they are both recycled glasses and their major and minor chemical compositions are very similar to that of 'pristine' Foy 2 glass. Just as the recycled Foy 2 glass was the dominating compositional group of vessel glasses from early medieval Dutch sites, the recycled intermediate glass was also the dominating compositional group for glass of 7th–11th century dates found at Comacchio, northern Italy (53 out of 77). However, in the two studies only a very limited number of 'pristine' Foy 2 glasses have been identified. This phenomenon suggests that 'pristine' Foy 2 glass would have been the main raw glass imported to the two areas for glass working prior to or in the early part of the period. However, after this supply waned, local glass working in the two areas had to rely more on recycling contemporary cullet and old Roman tesserae.

The chemical compositions of glass from Comacchio and from the early medieval Netherlands also reflect some differences in the supplies of raw glass. First of all, Levantine glass was one of the important sources of raw glass in Comacchio, possibly after the 'pristine' Foy 2 glass supply waned in the area, but not in the Netherlands. Altogether 17 pristine Levantine glass samples were identified from the total of the 77 items analysed from Comacchio.[334] This is a proportion that is much higher than the number (four) of 'pristine' Foy 2 samples found at the site. Besides, the chemical compositional features of mixing Foy 2 glass with Levantine glass were also noted in the intermediate glass group, which suggests that apart from Foy 2 glass, Levantine glass was another source of glass contributing to the recycling process.

331 Bertini, Henderson & Chenery 2020.
332 Schibille *et al* 2022.
333 Bertini, Henderson & Chenery 2020.
334 Bertini, Henderson & Chenery 2020.

In contrast, apart from one punty glass fragment from Wijnaldum (WIJ 42), no pristine early medieval Levantine glass was found amongst the samples analysed here, and no mixing with Levantine glass can be suggested from the chemical compositions of the predominantly recycled Foy 2 glass found here. Analysis of glass from another contemporary site in the southern Mediterranean, Tolmo de Minateda (Spain), also revealed the presence of a higher proportion of Levantine I glass (33 out of 253 samples).[335] Therefore, we can be sure that pristine Levantine natron glass did not arrive in the Netherlands in the relatively large quantities that reached northern Italy and Spain. Secondly, no wood ash glass was identified amongst the 7th–11th century Comacchio glasses analysed. By the 9th–11th centuries, wood ash glass accounts for more than half of the samples tested from Deventer with the proportion of wood ash glasses found in contexts dating to after 900 increasing somewhat, perhaps as a result of the Viking trade network. Wood ash glass was almost entirely dominant in the manufacture of a range of glass vessels by the 10th century in France with minimal recycled natron glass.[336] Therefore this shows that wood ash glass found in northern, western and central Europe may not have been available in Comacchio and other sites in northern Italy[337] during the period, just as Levantine glass may only have had very limited availability in the early medieval Netherlands. No wood ash glass was found at the 9th to 13th century glass from the site of Siponto in southern Italy[338] and only plant ash glass was being manufactured by the 13th-14th century at the northern Italian site of Germagnana.[339]

Moreover, six pieces of Egyptian II glass have been identified amongst Wijnaldum, Dorestad and Deventer glasses. The three Deventer examples all contain lower levels of Li, R, Cs and Ba than detected in contemporary recycled Foy 2 glasses discussed above reflecting their 'pristine' nature. Although Egyptian II do not account for a high proportion of the total glasses analysed, they are the only 'pristine' natron glass found from the 8th century and later with only an 'anecdotal' occurrence in France.[340] This could mean that amongst the limited amount of 'pristine' natron glass that arrived in the Netherlands during this period, Egyptian II glass was quite important. Moreover, no Egyptian II glass was identified amongst 7th–11th century glass vessels from Comacchio even though a higher proportion of Egyptian II glass was found in the Levant after the 9th century.[341]. This therefore reflects an important contrast in the availability of raw glass in northern Italy and the Netherlands and it also partly reflects a collapse in Mediterranean trade.

5.10.6 Wood ash glass and mixed alkali glass

Wood ash glass and mixed alkali glass are treated as one group here because they were both produced using wood ash as one important raw material. All wood ash glass and mixed alkali glass identified came from Carolingian sites: two wood ash glasses from Dorestad, one wood ash glass and one mixed alkali glass from Susteren, and twenty four wood ash and mixed alkali glasses from Deventer. Their dates are all later than the end of the 8th century, which is in line with the date that wood ash glass technology emerged in northwestern Europe.[342] We have also noted above that wood ash glass may already have been involved in glass recycling in the Netherlands as a minor component during the Carolingian period as suggested by the clearly elevated Rb and Cs contents of the recycled glass from Dorestad, Susteren and Deventer (see Section 5.10.4).

However, the proportions of wood ash in all the glasses studied from the three sites are quite different. In Dorestad and Susteren, wood ash glass and mixed alkali glass only account for a very small fraction of early medieval glass, while in Deventer wood ash glass and mixed alkali glass make up two thirds of the total vessel glass from the site. This difference can largely be attributed to the dates of glass samples from the three sites. The glass from Dorestad and Susteren dates to between the 7th and 9th centuries, while the glass from Deventer dates to between the mid-9th and mid-11th centuries. This suggests that the supply of wood ash and mixed alkali raw glass was quite limited in the Netherlands during the late 8th century and early 9th century and that they are likely to have formed a significant part of the raw glass supply from the mid-9th century onwards.

335 Schibille *et al.* 2022.
336 Pactat 2021, Fig 7.
337 Cagno *et al.* 2012.
338 Genga *et al.* 2008.
339 Casellato *et al.* 2003.
340 Pactat 2021.
341 Phelps *et al.* 2106.
342 Krueger & Wedepohl 2003.

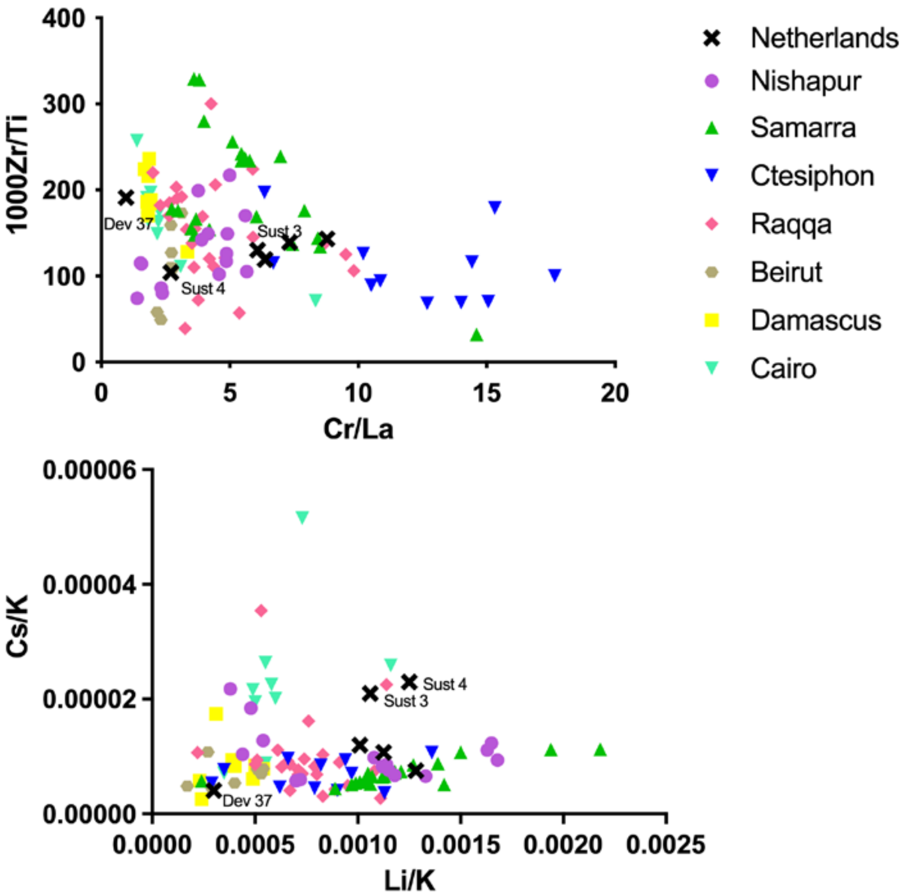


Figure 5.28 Plots of Cr/La against 1000Zr/Ti ratios (top) and Li/K against Cs/K ratios (bottom) of plant ash glasses from Deventer and Susteren (labelled) and Wijnaldum compared to data published previously. Data source: Henderson *et al.* 2016.

5.10.7 Plant ash glass

Altogether only six plant ash glasses were identified from all the glass analysed here. They are four glass beads, WIJ 35 and WIJ 37 (a gold foil and a silver foil bead), Sust 3 and Sust 4 (both trail decorated conical beads) and two glass vessels, Sust 28, a pale green funnel beaker and Dev 37, a possible beaker fragment. It is difficult to give clear provenance identification for plant ash glass by using major and minor chemical compositions alone. However, by plotting certain key trace element values[343] (Cr/La against 1000Zr/Ti and Li/K against Cs/K) found in plant ash glass samples along with a large dataset of plant ash glasses of different origins from the Middle East,[344] we can provide some clues about the possible origins of our samples (Figure 5.28).

From the two plots using key trace element ratios we can see that three samples (WIJ 35, WIJ 37 and Sust 28) cluster together in both plots. Sust 3 clusters together with WIJ 35, WIJ 37 and Sust 28 in the Cr/La versus 1000Zr/Ti plot and with Sust 4 in the Li/K versus Cs/K plot. Dev 37 clearly has a rather different trace element composition from the remaining five samples. In terms of the origins of the plant ash samples, we can see WIJ 35, WIJ 37 and Sust 28 basically cluster closely with samples from sites located in the eastern zone of Western Asia, in Iraq and Iran: Nishapur, Ctesiphon and Samarra. The Nd–Sr isotopic ratio of WIJ 37 also clusters with Sasanian glass samples from Veh Ardašīr, 40 km to the southeast of modern Baghdad, Iraq (see Section 5.9) providing a geological provenance so this agrees with the trace element results.

Therefore we can suggest that WIJ 35, WIJ 37 and Sust 28 originated from the eastern zone of Western Asia. Dev 37 clusters closely with samples from Damascus in both plots and

343 The approach was taken by Henderson *et al.* 2016.
344 Henderson *et al.* 2016.

therefore derives from the Levantine region. Moreover, it can be suggested that Sust 3 was made in the eastern zone and Sust 4 possibly northern Syria, though this is not entirely clear.

5.11 Summary

The analytical results for the early medieval glass samples studied have provided new insights, especially into two aspects of the glass used and manufactured in the Netherlands, namely the highly coloured opaque monochrome glass beads produced in 6th-7th century AD Netherlands and changes in the glass supply in the period between the late 4th century and mid-11th century AD.

The analysis of the materials used to make coloured beads from the Jodenstraat site in Maastricht has confirmed the previously suggested two-step manufacture mode for coloured bead making (see Section 5.10.1) and on-site lead-tin yellow colorant production at the site (see Section 5.10.2). Our new understanding from analysing these materials is that 'pristine' Foy 2 glass was used as the base glass for making beads at Jodenstraat (see Section 5.10.1) and that the tin opacifiers, to make both yellow and white glass, used in making coloured beads were also produced on-site (see Section 5.10.3).

The majority of glass analysed was imported, and our aim in analysing it was mainly to identify its chemical compositional group. We have managed to group the glass according to its compositional features for the majority of the glass analysed and we have also identified shifts in glass supply in the Early Medieval Netherlands according to changes in glass compositional groups over time (see Section 5.10.4 and Section 5.10.5). The political and economic factors probably responsible for the shifts in glass supply to the Early Medieval Netherlands are addressed in Chapter 6, along with evidence from other historical studies.

6 Synthesis and conclusions

6.1 The Early Merovingian period (450-550 AD)

McCormick[345] considers that the study of textiles, relics and coins, but also glass and ceramics, are a good way to disentangle the complexities of the early medieval economy. Our scientific results for glass help to unravel some aspects of the early medieval economy in the Netherlands and build on the established picture for the production and supply of early European glass. The early Merovingian period dating to between 450 and 550 AD saw important economic, social and cultural developments under the Pippinids in the Meuse valley. The glass in use was essentially a continuation of the Roman tradition but with a reduction in the range of production techniques for vessels. It mostly involved translucent blue-green nearly colourless hues for vessels and there was a continued import of glass beads from the Mediterranean. There is some evidence that glass beads were made in Cologne. Bowls, cups, bottles and cone beakers sometimes with trail decoration, including the famous Kempston type,[346] date to this period.

There is evidence for a workshop at Huy in the Meuse valley where glass was worked but no evidence for the types of objects/vessels made there has been found.[347] There is also evidence for Rhenish production[348] with possible evidence in Cologne[349] and concentrations of early Frankish vessels around Mayen (Eifel) might suggest a production centre in the area.[350] Furthermore a possible production site for 5th century Helle bowls has been found in western Germany at Asperden[351], quite close to Gennep, where some were discovered.[352] It is possible that glass vessels were made in the proto-urban centre of Maastricht at this time.[353] So the glass vessels found at Maastricht and certainly those found at Gennep studied here would have been imported from one or more of these places.

The glass that we have analysed dating to this phase mainly derived from Gennep, with two vessels from Wijnaldum. By determining major, minor and trace levels of element oxides in glass vessels from Gennep dating to between the late 4th and mid 6th centuries we have found the use of (pristine) HIMT *sensu stricto*, Foy 2, and quite early examples of *recycled* Foy 2. HIMT glass was probably made in Egypt[354] from the mid 4th to the 5th centuries and Foy 2 also probably had an Egyptian origin from the second half of the 5th and the 6th centuries. Therefore, raw furnace glass would have been imported to centres on the Rhine and Meuse to be remelted and worked/blown into vessels. Glasses would also have been recycled on these secondary production sites though no crucibles in which evidence for such glass mixing have been found.

There are some interesting relationships between compositional type, colour and vessel type for Gennep vessel glasses. Four cone beakers are made from pristine HIMT, three of which are decorated with spiral coils below the rims. Seven other cones were made from recycled Foy 2 glass. Whereas the Foy 2 glass is very pale green 'colourless' or pale green, the HIMT glass cones are olive-green, yellow-green and amber-brown due especially to higher levels of iron and manganese. Pristine Foy 2 was used to make four bowls with vertical loops below an outfolded rim, similar to the decoration on Kempston cones; pristine Foy 2 was not used to make cone beakers in our data set. It appears therefore, that a specific supply of pristine Foy 2 glass was used to make the bowls we have analysed from Gennep; single examples were made from pristine HIMT and recycled Foy 2 glass. Of the five bowls from Gennep decorated with an opaque white feather pattern that we analysed, four are of recycled Foy 2 glass and the fifth made from pristine Foy 2. Both cone beakers and bowls were made with nearly colourless (very pale green) recycled Foy 2 glass, including the two cone beakers from Wijnaldum dating to this phase, one a Kempston cone.

Therefore, the majority of cone beakers at this site/time were made from pristine pale green Foy 2 glass or more deeply coloured yellow-green and brown pristine HIMT glass. In contrast the majority of 'colourless' bowls decorated with feather patterns and some 'colourless' cone beakers were made from recycled Foy 2 glass. Perhaps unsurprisingly this suggests that colour was an important consideration when it came to pale green or nearly colourless drinking vessels made from Foy 2 glass, where the colour of the liquid could be observed depending on whether beer or wine was being consumed. Nevertheless, the use of strongly coloured olive-green, yellow-green and amber-brown Egyptian HIMT glass to make cone beakers suggests something else. It is possible

345 McCormick 2001, 281.
346 Evison 1972.
347 Van Wersch 2013.
348 Koch 1987.
349 Dodt, Kronz & Simon 2021.
350 Sablerolles 1993.
351 Brüggler 1994.
352 Sablerolles 1992, Sablerolles 1993, Henderson 2000, 68-70.
353 Van Lith & Sablerolles 1995.
354 Arles *et al.* 2019.

that glassblowers used whatever came to hand but we have nevertheless found evidence for a relationship between vessel type and colour so probably some vessels were made in batches using raw glass of the same colour.

Unstable Merovingian vessels such as bell beakers, palm cups and deep palm cups as well as Carolingian funnel-shaped and pointed conical beakers are usually interpreted as drinking vessels which had to be emptied before placing them upside down. Indeed, illuminations in several Carolingian manuscripts show the use of 9th century glass cones as wine glasses.[355] In Viking period graves and settlements the association between glass funnels and cones and fine ceramic tablewares such as Tating jugs and Badorf pitchers also indicates a drinking function.[356] However, an illustration in the First Bible of Charles the Bald, also known as the Vivian Bible, after Count Vivian of Tours who commissioned the bible in 845, shows the use of individually suspended glass cones as lamps.[357] It appears that these Carolingian glass vessels were multi-functional. The same is probably true for unstable Merovingian glasses with rounded bases. Experiments with bell beakers, palm cups and deep palm cups have led researchers to believe that all these vessel types could have been used as lamps.[358] Van Winkelhoff found that mould-blown and optic blown vertically ribbed glass vessels were especially effective in that they emitted bright and clear “sunlike” patterns and that small mould-blown palm cups work especially well as lamps when hung at a low level above the ground.[359] She concluded that such usage is especially relevant in the context of a grave lamp, or votive lamp, hung as a visual reminder of the deceased at the grave.

Although raw pristine HIMT glass imported from Egypt would undoubtedly have passed through intermediaries before being blown into vessels, perhaps its exotic origin was still known and was socially and/or ritually significant depending on whether it was used in a domestic context or in a burial. Six beads and a greenish-white glass breaking splinter from Wijnaldum date to this phase. Two beads are colourless with gold and silver-foil respectively.
They appear to have been made using pristine Foy 2 glass, adding to the evidence for a much higher proportion of pristine glass in circulation in the early Merovingian period than in the Carolingian period. Out of the six beads a single opaque yellow one is opacified with lead stannate so dates to before the evidence of the production of such glass in Maastricht; the breaking splinter is opacified with calcium antimonate in the Roman tradition found in tesserae.[360]

6.2 The Middle Merovingian period (550– 650 AD)

In our second period dating to between 550 and 650 AD the production of glass vessels became somewhat diminished, with a reduction of vessel types. For some reason beads were no longer imported from the Mediterranean and this seems to have led to the birth of Merovingian bead production,[361] which saw massive numbers of glass beads being manufactured with very similar designs. These were distributed across Europe between the Anglo-Saxon realms, the Merovingian territories as well as the Frankish kingdom of Italy[362] as late as the end of the 7th century. So, much imported glass would have been used to make beads.[363]

In the Netherlands, glass beads, especially opaque yellow ones, were being manufactured in Maastricht, with especially good evidence for their production dating to between the late 6th and early 7th century at Jodenstraat, Maastricht, located well within the Merovingian empire. Comprehesive evidence for bead making has also been found at the central places of Rijnsburg Abdijterrein on the Rhine delta and Wijnaldum-Tjitsma, a northern terp site. Both of these two sites are located well outside the border of the Merovingian empire so there was clearly a demand for fashionable beads outside the empire; a local ruler may well have invited a bead maker to the sites. The bead making evidence at all three sites dates to the last quarter of the 6th and first half of the 7th centuries AD.

We have found evidence for the manufacture of lead tin yellow (lead tin yellow II) for colouring glass in a number of crucibles at Jodenstraat, Maastricht. The occurrence of silica crystals associated with this yellow pigment, as well as pure lead-silica glass in eight crucibles, is clear evidence for the second step in the production of lead tin yellow II when it was added to the lead tin calx.[364] The first step in the production of lead tin yellow II – the production of lead tin calx

355 Biblioteca Apostolica Vaticana, Rome, Ms. I. Cod. Reg. Lat. 438, 25r (https://digi.vatlib.it/view/MSS_Reg.lat.438/0053). Bibliothèque nationale de France, Paris, Département des Manuscrits, Lat. 8085 fo 61v. https://portail.biblissima.fr/ark:/43093/mdata69093fcda745577-d3ff9d21597dc3fc4c51ca346. Special Collections University Library Leiden, Codex Burmanni Q 3, folio 120v. (https://disc.leidenuniv.nl/view/item/1935754?solr_nav%5Bid%5D=-22d3ef11949c6ef5312f&solr_nav%5Bpage%5D=0&solr_nav%5-Boffset%5D=0#page/138/mode/1up).
356 See for instance Arbman 1937, 41-44, fig. 5a-b; Gaut 2011, 194, 255-265.
357 Aunay, *et al.*2020, 298 (Paris, BnF. Ms. Lat. 1, f327v).
358 Later 2010; Van Winkelhof 2021.
359 Van Winkelhoff 2021.
360 Henderson, Sode & Sablerolles 2019.
361 Pion 2014.
362 Boschetti, Gratuze & Schibille 2020.
363 The Rural Riches project funded by the European Research Council (ERC) of the European Union, and directed by Professor Frans Theuws is investigating the sources and distribution of such beads.
364 Matin 2019.

– would have happened elsewhere (perhaps even in Maastricht), but not in the crucibles we have examined. The same evidence for the manufacture of lead tin yellow glass in a tray, dating to between 575 and 625, was found at Wijnaldum.

The yellow pigment was made in what was originally 6th–7th century Merovingian wheel-thrown ovoid-shaped domestic coarseware storage pots which would have had a constricted opening and an everted rim. The top half of the pot was taken off for the production of the yellow pigment.

This production process for opaque yellow glass is described in later Islamic literature, the earliest being Abu'l Qasim Kashani dating to 1301.[365] No lead-silica glass is in use for the manufacture of vessels or, by itself, for the manufacture of beads at the time.

We have found direct scientific evidence linking the crucible yellow glass to the yellow beads and yellow rods at Maastricht so they are clearly part of the production process there. The yellow beads and rods are united compositionally because a pristine Foy 2 base glass was used to make them. Translucent glass vessel fragments and wasters from Maastricht Jodenstraat were also made with pristine Foy 2 natron glass. Had the Roman vessel glass fragments found at Jodenstraat been used as a base glass instead this would have been detected, but this is not the case. Although similar evidence for the production of opaque yellow lead tin colourant has been found elsewhere,[366] including at Wijnaldum (discussed here), the Maastricht evidence constitutes the best evidence for its production in terms of its scale and for its use for making beads in north-western Europe. Quite why there was this demand for yellow glass beads is an intriguing question. No evidence for the production of opaque yellow glass in crucibles has been found in Carolingian contexts in the Netherlands.

Further new evidence for the production of opaque glass is for the manufacture of a tin white opacifier, found in two crucibles from Maastricht, Jodenstraat. This is the first evidence for this from northwestern Europe. We have also demonstrated that it was used to make the white, red and greenish glass beads at Jodenstraat, including their characteristic microstructures and the use of the same base natron glass, Foy 2. No crucibles in which the white pigment was mixed with base glass have been found. Whole pots, for which there is production evidence from Maastricht itself, were used for working translucent glass from both the Jodenstraat and Mabro sites in Maastricht, and also in Utrecht.

Detailed investigation of the 'frit-like' material observed on the rim of a crucible dating to the late 4th-early 5th century from the Mabro site in which translucent greenish glass was reheated, which would be tentative evidence for primary glass production[367], has instead been shown to have a variable composition and to be fuel-ash slag.

Seventeen of the beads from Wijnaldum date to this phase. Like the Maastricht Jodenstraat beads they were made from highly coloured opaque yellow, white and red glass. Their lead-rich chemical compositions, the colourants and the opacifiers used, as well as the evidence for the use of a pristine base glass, are all very similar to Maastricht beads. Two later (8th–9th century) gold and silver-foil decorated colourless plant-ash glass beads from Wijnaldum are discussed below.

Bead makers were evidently located in proto-urban or urban centres in the Meuse valley. This is in contrast to the situation further north where the relatively small scale of production suggests that bead makers travelled to centres like Wijnaldum, Rijnsburg and perhaps Valkenburg-De Woerd. Evidence for the manufacture of very popular Merovingian bead types with crossed swag decoration have been found at Rijnsburg, one of the types being found as far south as Italy. Callmer[368] has suggested that glass bead production was regarded as having a magical aspect at the time. If magic was considered as important, perhaps this is one reason why beads were no longer imported.

6.3 The Late Merovingian period (650 – 750 AD)

By 650–750 AD fewer glass beads were made; there was a restricted range of rather poorly made vessel forms, such as palm cups and deep palm cups usually made with poor quality bubbly glass full of inclusions, reflecting the high level of recycling. A further reduction in imported beads was a catalyst for more beads to be manufactured, especially in Scandinavia. The artefacts that we

365 Allan 1973; Matin 2019.
366 Henderson & Ivens 1992; Peake & Freestone 2014.
367 Sablerolles, Henderson & Dijkman 1997.
368 Callmer 2003.

have studied from this period are four opaque (yellow, red, orange and white) glass beads from Wijnaldum though these beads were probably made earlier than their context dates.

6.4 The Carolingian period (750 – c. 850 AD)

The Carolingian dynasty (750–887 AD) saw a renaissance in vessel production, especially with the use of new decorative techniques particularly in northern France, but also with clear evidence for the manufacture of pale green beakers from the Rhenish area with an expansion in the scale of production. It is also possible that highly coloured vessels were made in monasteries in the Netherlands. The vessels produced in France included globular jars and reticella decorated beakers: there is evidence for the production of lead-tin yellow pigment and its use in reticella rods to decorate glass vessels from the early 8th century site of Hamage, northern France.[369] This must have created different markets for both simple and more highly decorated vessels. Although the glass-working evidence for the Carolingian period is scantier, a contrast with the Merovingian period is that it occurs on a wider range of site types, including the emporium of Dorestad and the ecclesiastical centres of Susteren-Salvatorplein and Utrecht-Domplein. Wearing glass beads became less fashionable in the Frankish heartlands though they were still worn in the northern periphery of the empire. From the end of the 8th century onwards Islamic glass beads were imported via Viking trade networks and occur in settlements along the Rhine and in cemeteries north of the Rhine. The availability of Islamic glass beads may well have impacted on the manufacture of Frankish glass beads.

By this time the evidence for glass recycling had increased, with a much higher proportion of weak HIMT/recycled Foy 2 glass in circulation, with few examples of HIMT or other pristine glass types. Our analyses of fifty-five samples of palm cups, palm funnels (including a gold-foil palm funnel), bell beakers, funnel beakers and a bowl from Dorestad, as well as a Kempston cone, a bowl and four funnel beakers from Wijnaldum, show that, with a few exceptions, those who made these vessels relied on a supply of recycled (Foy 2) natron glass. The same is true for the Carolingian vessel glass from Susteren. Therefore we have assembled very strong evidence for recycled Foy 2 glass being the dominant glass type in the 8th and 9th century Netherlands, with pristine glass, especially Foy 2, having almost gone out of use.

The few exceptions are the use of Egyptian II glass used to make a possible pale green funnel beaker from Dorestad, and the latest dated funnel beakers from Wijnaldum (770–900): one is a dark blue incalmo rim, the other a blue-green colour. A single pale green funnel from Susteren was made with pristine HIMT. The only pristine Levantine (II) glass found in this study is a turquoise punty dating to 750–800 from Wijnaldum. So even when recycling was such a dominant practice at this time, a small amount of pristine glass was in circulation and would have been imported in raw form and made into funnel beakers at production centres.

This was a period of technological transition when the first European wood-ash glass was being manufactured and used to make vessels such as those from Baume-les-Messieurs,[370] and the possible production of mixed-alkali glass by extending natron glass with wood-ash (glass) at Méru, France.[371] Reflecting this period of technological transition, two wood-ash-lead linen smoothers (partly made using slag from silver smelting)[372] and two yellow-green wood-ash palm funnels derive from Dorestad, and a single piece of wood-ash blue-green window glass from Susteren. A single mixed-alkali pale green funnel was also found at Susteren. Raw wood-ash and mixed-alkali glass used to make the vessels would have been made more locally.

By using trace element analysis we have demonstrated that there was an increase in the levels of, for example, potassium and phosphorous oxides over time. Even though these are initially at low levels in the 8th–9th centuries, we have suggested that this indicates that a small proportion of wood-ash was being mixed into the (recycled) Foy 2 glass (referred to by Foy *et al.* as Foy 2.2)[373] from the late 8th century and into the Carolingian empire. This is supported by the occurrence of elevated trace levels of cesium, barium, rubidium and strontium in Foy 2 glass after the 8th century, all characteristics of wood-ash glass.

We have also demonstrated that this is the case with the first neodymium and strontium

[369] Lassaunière *et al.* 2016.
[370] Van Versche *et al.* 2015.
[371] Pactat *et al.* 2017.
[372] Pactat *et al.* 2017.
[373] Foy *et al.* 2003.

isotope analyses of recycled Foy 2 glass and observed that a probable explanation for an increase in the strontium isotope ratio (when compared to pristine Foy 2 glass) can be attributed to the mixing in of a small proportion of wood-ash glass. These compositional and isotopic results reflect the emergence of the first European-made (wood-ash) glass technology. The main evidence for early wood-ash glass production zones, based on the occurrence of dated glass objects, is in France and Germany.

Previous research has pointed to potential evidence for the addition of wood-ash glass to natron glass in Anglo-Saxon vessels from Jarrow,[374] and Ares *et al.*[375] have noted that a 'plant ash' component must explain the elevated levels of potassium, magnesium and phosphorus oxides above those found in natron glasses. Nevertheless, elevated levels of these elements could also be introduced into glasses with the addition of a small proportion of fuel-ash slag, also ultimately with a wood-ash component, as seen in the analysis of material attached to a crucible rim from Maastricht Mabro (crucible 9). It is however more than a coincidence that increasing levels of potassium and phosphorus, and especially elevated concentrations of cesium, rubidium, barium and strontium are correlated with a time when wood-ash glasses were being introduced in Europe, so this is a far better explanation.

Window glass with a full wood-ash composition has been found at the monastery of Baume-les-Messieurs, Jura in France[376] dating to the late 8th century. It is possible that the presence of small proportions of wood-ash (glass) in recycled Dutch early medieval natron glass resulted partly from wood-ash glass production further south in Belgium and France – and we suggest that a source to the east in Germany as mentioned in Chapter 2.4.1 is more likely. There is no early medieval wood-ash glass making evidence from the Netherlands.

We have compared our results with those from Comacchio in northern Italy[377] and observed some intriguing differences. In Comacchio a far higher proportion of pristine Levantine glasses was identified (17/77). This compares with a single example amongst our data: a punty glass from Wijnaldum. The mixture of Levantine and Foy 2 glass from Comacchio led to an 'intermediate' group being recognized. No examples of wood-ash glass were found at Comacchio, nor evidence for its mixture with natron glass. We are therefore the first to define these contrasting production spheres using the characteristics of recycled glasses: a southern European one exemplified by Comacchio glass and Spannish glass from Tolmo de Minateda[378], with far greater evidence for the use of Levantine glass, and a northwestern European Dutch one with a reliance on an admixture of wood-ash glass and no apparent evidence for mixing with Levantine glass. Our approach could be used to define recycling traditions, reflecting trade links, in other parts of Europe.

The manufacture of the first European (wood-ash) glass would have partly been driven by the demand for windows in monasteries and churches: by the 10th century it is therefore no coincidence that wood-ash glass was being worked at the ecclesiastical site of La Milesse, Sarthe in France. In our study nine out of the eleven window glasses analysed from the monastic site of Susteren are of a natron composition – seven are recycled Foy 2, and the single example of Egyptian II noted above. This is further evidence for very different glass supply in the two areas.

From the early 9th century another type of glass was made, from ashed halophytic plants and sand in Islamic cosmopolitan centres in western Asia. Although the Sassanids had made plant-ash glass earlier there is no current evidence that it was used to make glass objects in western Europe. Trace element analysis has shown that the manufacture of plant-ash glass by the Muslims formed part of a decentralized production system[379] and that it is possible to link quite securely the provenance of Islamic plant-ash glasses to production centres or zones. A gold-foil bead (dated 775–850 AD) and a silver-foil bead (dated 875–900 AD) from Wijnaldum are plant-ash glasses imported from western Asia; the bodies of two rather unique trail-decorated conical beads and a blue-green funnel from Susteren are also made of plant-ash glass.

The Susteren beads and beaker would have been made in the west using raw plant-ash glass imported from western Asia. A probable funnel beaker fragment of a west Asian plant ash composition from Deventer was found in a context dated to between 950 and 1050 AD. Trace element analysis shows that the metal foil beads from Wijnaldum were probably made in

374 Freestone & Hughes 2006.
375 Ares *et al.* 2019.
376 Van Wersch *et al.* 2015.
377 Bertini, Henderson & Chenery 2020.
378 Schibille *et al.* 2022.
379 Henderson *et al.* 2016.

the eastern zone of Western Asia, in Iraq/Iran. The glass used to make the two Susteren beads probably derived from Iran/Iraq, and possibly northern Syria, respectively. One of the Susteren beads (Sust 4) is decorated with opaque white glass produced in the Roman tradition (calcium antimonate crystals) used almost universally in Roman glass tesserae. Therefore the bead combines an intriguing combination of western European and west Asian traditions. The raw plant-ash used to make the Deventer vessel (fragment) derived from the Levant. The import of raw plant-ash glass probably formed part of the Viking trade network via centres like Hedeby. Though only plant ash glass beads have been reported so far, the occurrence of mixed plant ash and lead glass at Hedeby provides indirect evidence for the import of raw plant ash glass.[380]

The occurrence of other Islamic artefacts made from plant-ash glass is further evidence of such a trade network. Examples are the import of large numbers of early Islamic glass beads to Scandinavia from the late 8th century and later in Viking-age contexts such as in Gotland burials,[381] from precision-dated excavations at Ribe, Denmark[382] and millefiori decorated glass beads from Dorestad.[383] No examples were found at Borg in Norway[384] but five plant ash glass beads were found at Kaupang.[385] Early Islamic glass beads are found along and to the north of the Dutch Rhine, along the German Wadden sea and on the Baltic coast. However minimal numbers have been found along the German Rhine or in Belgium and France. An exception is the occurrence of 9th century small glass bottles made from plant-ash glass imported from Islamic lands,[386] which were probably used for the import of specific western Asian liquids. The relative rarity of Islamic plant ash glass in France at this time may be because the demand was lower, due to the greater availability of wood-ash and mixed-alkali glass. However, a better explanation is that France and Belgium did not form part of the Viking trade network that existed to the north. Further south, in Umayyad Spain, plant-ash glass was imported from western Asia in the 8th and 9th centuries; [387] Islamic glass beads dominated amongst those found at Illyricum, Albania.[388]

6.5 The late phase, including the Ottonian period (c. 850 – c. 1000 AD)

The last phase (850–1000) was a time when very few glass beads were produced in the Netherlands apart from evidence of small-scale production at Dorestad. It includes the Ottonian Dynasty (919-1024 AD). Beads were imported from Scandinavia and continued to be imported from Islamic western Asia. This phase is represented in our research by glass from Deventer. The site produced a wide range of glass compositional types: nineteen wood-ash glasses, one pristine and five recycled Foy 2 glasses, four mixed-alkali glasses, three Egyptian II (natron) glasses, three Roman (natron) glasses and one plant-ash glass. A single example of high lime -low alkali window glass is potentially a very early example of what is generally considered a much later technology though it appears there are other early examples from east of the Rhine.[389] Funnel beakers and conical beakers were the dominant vessel forms in the second half of the 9th and the 10th centuries. By this time the vessels from Deventer were made out of wood-ash glass, recycled Foy 2 glass, plant-ash glass and Egyptian II glass. This shows that they were blowing these vessels from whatever was available; unless the different sources of natron glass were known (which is a possibility for pristine glass) the different origins of pale green recycled natron glass – potentially with different working properties - would normally be unknown. The wood ash and natron glasses would certainly have had different working properties: thick-walled wood ash glass vessels started to replace the thin walled Carolingian beakers after *c.* 900 AD. A single chunk of raw Egyptian II and three chunks of raw wood-ash glass were found on the site. This could constitute tentative evidence for a glass industry there, or it could simply mean the glass was being traded through the site.

The use of fresh high quality Egyptian II glass for the manufacture of funnel beakers is in contrast to the preceding phase when a very high proportion of recycled glass was in use, for example to make the funnel beakers found at Dorestad. Apart from the four definite examples of wood-ash funnel beakers from Deventer (two dating to the late 9th century), there is an

380 Kronz *et al.* 2016.
381 Thedéen 2009.
382 Philippsen *et al.* 2021.
383 Langbroek 2021b.
384 Henderson & Holand 1992.
385 Gaut & Henderson 2011.
386 Pactat 2021.
387 Schibille *et al.* 2020.
388 Neri, Gratuze & Schibille 2018.
389 Pers. Comm Professor Kronz.

8th–9th century palm funnel from Dorestad,[390] as noted above, with another nine examples from Hedeby.[391] As is to be expected, many were very poorly preserved. The balance of the Hedeby funnel beakers analysed were twenty natron (Foy 2) and one mixed-alkali glass.

In contexts dating to the 9th and 10th centuries at Deventer 60% of the glasses were wood-ash or mixed alkali glass. These would have been manufactured as part of a decentralized production system.[392] Some of the earliest full wood-ash glasses have been found at Stavelot in Belgium and at Baume-les-Messieurs, Jura in France. It also seems to be the case that France was a centre for the production of mixed-alkali glass (and perhaps wood- ash glass), one probable location being Méru, France. In contrast to Deventer, by the 10th century almost all glass found in France was of the wood-ash type.[393] Currently we do not know where the Deventer mixed-alkali or wood-ash glasses were made. Although France is one possible source for Dutch wood-ash glass a more likely one was the Viking trade network including through Hedeby, perhaps from northern Germany, for example, where funnel beakers and a crucible containing wood-ash glass have been found.[394] The higher proportion of non wood-ash glass found in 10th century Deventer, including pristine Egyptian II glass – and possible working debris- also contrasts with the situation in France, suggesting that a separate supply route from Egypt was involved, probably including several intermediaries.

390 Henderson 2012.
391 Kronz *et al.* 2016.
392 Meek, Henderson & Evans 2012; Van Wersch *et al.* 2015; Adlington *et al.* 2019.
393 Pactat 2021.
394 Kronz *et al.* 2016.

7 Answering the research questions

In the introduction to this book a series of research questions were posed. In this chapter we discuss the extent to which we have been able to answer them.

1. What raw materials were used in the local production of simple, monochrome Early Medieval glass beads?

We have been able to identify the base glass used in the manufacture of monochrome yellow, white, red, and blue beads as a type of natron glass, Foy 2 (see Section 5.10.1). No base glass was fused from raw materials in the early medieval Netherlands, so it needed to be imported (see below). The majority of the material examined scientifically that is relevant to this research question forms part of some of the most comprehensive evidence for the manufacture of such beads in early medieval northwest Europe, from Merovingian Maastricht at the Jodenstraat site dating to the late 6th-early 7th century. The evidence consists of beads, broken beads, rods, drops - and crucibles with evidence for the manufacture of the opaque yellow and white pigments attached to them. The 26 trace element signature of the glasses, determined by laser ablation inductively coupled plasma mass spectrometry, showed that they are unified compositionally by being made with the same base glass: 'pristine' Foy 2.

The other raw materials which both coloured and opacified the glasses used to make the monochrome beads are the colorants. Tin-based pigments were made at Maastricht which were then used to make bright opaque yellow and white glass. The tin based opacifier was also found in red and greenish-blue coloured glass beads which, in all likelihood, were also made in Maastricht. A thick possible furnace or tray fragment from Wynaldum also has a thick layer of opaque yellow material attached to: it provides probable evidence for the manufacture of lead-tin yellow II pigment. Monochrome beads would have been made there too. A separate source of lead would have been involved.

Given that pristine Foy 3.2 glass (a sub group of Foy 2) was used to make the translucent blue bead and the four blue glass fragments found at Maastricht it is a possibility that the cobalt colorant was added to the base glass in Maastricht though, unlike the evidence for the manufacture of lead tin oxide II, there is no archaeological evidence for the manufacture of cobalt blue glass at the site. Nevertheless it would seem that the cobalt-rich colorant was added directly to the pristine base glass at some point.

2. Where were these raw materials obtained from?

Glass that has a Foy 2 trace element signature is very likely to have derived from Egypt. [395] It was made with silica sources that are characterised by the presence of minerals that introduced elevated elements such as titanium, manganese and iron. It is difficult to be certain where the tin used to make the opaque yellow and white glasses was derived from. Possible sources are in Cornwall in the UK[396] and Turkey.[397] Lead is a far more common mineral with possible sources in northern Spain, central and southern England, the Saxon-Bohemian metalliferous mountains (including the Erzgebirge) and Harz mountains in Germany[398], northern Italy and the Taurus mountains in Turkey. Lead isotope analysis has the potential to determine in an increasingly precise way the source(s) of the lead used when used in an appropriate way such as used for European iron age glass[399] and in ancient metal research.[400] The lead source used in early medieval Dutch glass would be introduced either as an impurity[401] or deliberately as part of a colorant, such as lead-tin yellow II. Therefore, lead isotope analysis could potentially source the lead raw material, but not the glass, as discussed below.

Sub-questions here are:

i. What substances were used to make the different colours of glass in the artefacts tested?

As noted above the monochrome opaque beads from Maastricht, Jodenstraat were mainly coloured with lead-tin oxide II and tin oxide. Tin oxide was also combined with copper and cobalt to produce opaque red and blue glass respectively. Examples of yellow glass opacified with lead-tin oxide II have also been identified in glasses found at Wijnaldum and Dorestad. Detailed analysis of the opaque red glass from Maastricht, Jodenstraat revealed the presence of micron-sized copper droplets, iron-rich fayalitic slag[402] and a crystalline phase containing high tin associated with lead and silica: the colorant is copper. The presence of micron sized copper droplets and fayalitic slag was also found in red beads from Wijnaldum.

395 Foy *et al*. 2003.
396 Meharg *et al* 2012.
397 Yener *et al*. 2015.
398 Wedepohl & Baumann 1997.
399 Huisman *et al*. 2017.
400 Artioli *et al*. 2020; Standish *et al*. 2021.
401 Henderson *et al*. 2005b.
402 Peake & Freestone 2012.

The pale green vessel glasses analysed were coloured mainly with a combination of manganese and iron oxides: if HIMT or one of its recycled variants was used as the base glass, elevated manganese (and iron) would have modified the final colour, partly depending on the melting atmosphere in the furnace. For example HIMT glass cones form Gennep are olive-green, yellow-green and amber-brown due to relatively high levels of iron and manganese. Other vessel glasses were coloured with cobalt producing a blue colour and ferrous iron has produced an amber colour. Deliberately added colorants/opacifiers for glasses in both Merovingian (Wijnaldum and Maastricht) and Carolingian glasses (e.g. Susteren glass beads) are very similar: elevated Fe oxide (up to around 5 weight %) and CuO_2 (up to around 1.7%) in red glass, high PbO and SnO_2 in opaque yellow (probably in the form of $PbSnO_3$ crystals) as well as a combination of Pb and Sb which responsible for opaque yellow glass (in the form of $Pb_2Sb_2O_7$ crystals).

Opaque turquoise and blue tesserae from Dorestad are coloured by copper and cobalt respectively. Three of the five are opacified with calcium antimonate. An opaque yellow glass rod from Dorestad (DOR149) has a similar chemical composition to opaque yellow glass from Maastricht, Jodenstraat and Wijnaldum. It has relatively high Na_2O (10.6%) and PbO (10.7%) contents and low K_2O and MgO contents: it is also coloured by lead tin yellow II. Therefore, it would have been made using the same procedure as the opaque yellow glass from Jodenstraat and Wijnaldum. The Al_2O_3/SiO_2, TiO_2/Al_2O_3 ratios and low Sb content of suggest that the base glass used could also have been 'pristine' Foy 2 glass.

ii. What compositional groups can be distinguished in the glasses based on chemical analyses?

The compositional groups that we have identified amongst the glass samples that we have chemically analysed are all known from the literature (see Section 2.4.1 for a full discussion of the glass types and associated literature).
By chemically and isotopically analysing recycled Foy 2 (natron) glasses which was the dominant composition between the early 8th century and late 9th century we have been able to provide a new explanation for some of the impurity levels detected in the glass in a new way (see Sections 5.9 and Section 5.10.4).

We have identified the following compositional types:
Natron (soda-lime) glasses:
- 'Roman'
- High iron, manganese and iron (HIMT)
- Foy 2.1
- Foy 2.2 (recycled glass)
- Foy 3.2
- Egyptian II
- Levantine II

Plant ash (soda-lime) glass
Mixed-alkali (sodium and potassium) glass
High potassium glass

iii. What does this tell us about dating of primary glass production of these groups?

There is no evidence for primary glass production in the early medieval Netherlands. It is known that glass of a 'Roman' composition was made between the 1st and 4rd centuries AD on the Levantine coast and in Egypt. Glass of the HIMT composition was made between the 4th and 5th centuries and it is probable that weak HIMT (HIMT-2 = Foy 2) was also made from around the mid 4th century though the recycled variants of HIMT/Foy 2 glasses have been found in much later contexts (see below) so will probably have been recycled multiple times. Glass of Foy 2.1 and 3.2 compositions were probably made from around the 6th century, the recycled Foy 2 (Foy 2.2) has been found in later contexts. Pristine Levantine II glass was made from the 8th century AD; Egyptian II was made between 760/780 and 870 AD.

Five Roman (vessel) glasses have been identified, from Jodenstraat Utrecht and Deventer. Our analyses suggest a Levantine source for this relic glass. A single Levantine II sample has been identified amongst our samples dating to between 750 and 850. Nintety-five mainly vessel glasses are of a recycled Foy 2 glass composition (corresponding to the Foy 2.2 group of Foy *et al.*).[403] Highly coloured opaque beads and translucent beads from Maastricht, Jodenstraat were made with pristine Foy 2 glass, as were the highly coloured opaque glass beads from Wijnaldum.

Nine HIMT *sensu stricto* glasses have been identified[404], six being from Gennep, the site with the earliest date (late 4th to mid-6th century) from which we have obtained samples.
Eight 'pristine' Foy 2 glasses have been

[403] Foy *et al.* 2003.
[404] Nenna 2014.

identified: six from Gennep and 2 from Maastricht, Jodenstraat, dating to between the late 4^{th} and early 7^{th} centuries AD. Six 'pristine' Egyptian II glasses have been found: two from Wijnaldum, one from Dorestad and three from Deventer. Using context dates, three from Deventer date to the 8^{th}–9^{th} centuries AD, two date to the early 10^{th} century and one dates to between 950 and 1050 AD. They are consistent with or slightly later than the suggested date when Egyptian II glass was widely circulated, in the 8^{th} and 9^{th} centuries AD. Previously it had been suggested that HIMT glass in the widest sense (including HIMT *sensu stricto* and Foy 2) was in use from the middle of the fourth century until the seventh century.[405] However, our results show that recycled Foy 2 glass (referred to as 'recycled Foy 2' glass in this study, corresponding to Foy 2.2 group)[406] was still the dominant compositional group between early 8^{th} century and late 9^{th} century in Dorestad and Wijnaldum vessel glasses. Moreover, it remained in circulation till possibly as late as the first half of the 10^{th} century according to our results from Deventer.

This shows that recycled Foy 2 glass was in use centuries after the 'pristine' Foy 2 glass supply dried up in northwestern Europe. The recycled version of Foy 2 glass is labelled as Foy 2.2 subgroup in the work of Foy and colleagues,[407] and is known from a very limited number of assemblages in France, Italy and Spain that are typically dated to the end of the seventh and into the eighth centuries AD.[408]

Twenty six wood ash/mixed alkali glasses have been found in this study. Two samples derived from Dorestad, two from Susteren and twenty-three from Deventer. These dates are consistent with the suggested date from when wood ash glass started to be made and was circulating in Europe from the late 8^{th} century onwards.

Six plant ash samples have been identified; all date to post-9^{th} century AD the time when plant ash glass started to be the dominant technology in western Asia. Islamic plant ash glasses started to appear further west and east after this time. Plant ash glass was used to make single funnel beakers from Susteren and Deventer, the bodies of two decorated trail-decorated beads from Susteren and it was formed into single examples of gold and silver foil beads found at Wijnaldum, imported from western Asia. Raw plant ash glass was therefore imported from western Asia to the west where it was remelted to form funnel beakers and some (trail-decorated) beads.

iv. What do the isotope ratios (Sr, Nd) obtained from the glasses of selected compositional types tell us about the their origin and dating?

Thirteen natron glass samples have a typical range of Nd–Sr signatures for such glass with εNd between -5 and -7, and $^{87}Sr/^{86}Sr$ between 0.7085 and 0.7093,[409] (Figure 5.24); one sample was contaminated (see below). The twelve clean natron samples are of the Foy 2 type: seven are 'pristine' Foy 2 glass and five are recycled Foy 2. Their $^{87}Sr/^{86}Sr$ ratios stretch in a rather wide range between 0.7085 and 0.7093. Six pristine' Foy 2 glasses form a cluster at $^{87}Sr/^{86}Sr$ of 0.7086, a typical value for glass produced in Egypt, the commonly suggested origin of Foy 2 glass. Five 'pristine' glasses are from bead making at Jodenstraat, Maastricht (late 6^{th}- early 7^{th} century AD), the 6^{th} being a gold foil bead from Wijnaldum. The $^{87}Sr/^{86}Sr$ of 0.7088 and 0.7093 for recycled Foy 2 (vessel) glasses all dating between the late 8^{th} to mid 9^{th} centuries AD is higher than the typical Egyptian range of values: it is likely that the $^{87}Sr/^{86}Sr$ values have been modified by the recycling process. We suggest that the mixing of wood ash glass, with very high $^{87}Sr/^{86}Sr$ values, with natron glass is the explanation; this agrees with the results from trace element analysis. We determined the Nd–Sr isotopic signatures for two wood ash-lead linen smoothers from Dorestad with very high $^{87}Sr/^{86}Sr$. A single plant ash glass, an Islamic silver foil glass bead has the lowest $^{87}Sr/^{86}Sr$ signature out of the 18 samples analysed and may have a provenance near Baghdad in Iraq. A single ribbed glass vessel and a glass tesserae are of 'Roman' chemical compositions and both have the anticipated typical Levantine natron isotopic signatures with $^{87}Sr/^{86}Sr$ values of 0.7090 and 0.7092 respectively.

v. What networks inside and outside the Netherlands were used in obtaining glass, including the colourants used?

In all cases it is difficult to ascertain how many intermediaries were involved during the process of obtaining glass, whether it was unworked 'pristine' raw glass, recycled raw glass or fully formed objects. The colorants used deliberately

405 Freestone *et al.* 2018.
406 Foy *et al.* 2003.
407 Foy *et al.* 2003.
408 Ares *et al.* 2019.
409 Brems *et al.* 2018.

(and their sources) which formed part of networks of interaction are discussed under question 2.

The source of many of the Carolingian beakers found in the Netherlands is considered to be Germany/Cologne. There is clear evidence that opaque yellow (and other brightly coloured) glass beads were made at both Maastricht and Wijnaldum, but there is still a possibility that beads found at Wijnaldum originated from Maastricht, for example. Lead may well have been obtained from Germany too; the tin source may potentially have been Cornwall in the UK or, less likely, Turkey.

Egypt was clearly the ultimate source for Egyptian II glass and pristine Foy 2 glass. Our isotopic results support an Egyptian provenance which, up to now, has mainly been suggested using the results of chemical analyses. There is little doubt that pristine HIMT glass was originally made in Egypt too, as recently confirmed using Nd and Sr isotope analysis, helping to distinguish it from Levantine glass.[410] There is a single example of an early medieval pristine Levantine glass in our study, underlining that the primary source of pristine glass for early medieval glass working was ultimately Egypt.

Plant ash glass would have been obtained from western Asia and using trace element analysis we have determined that northern Syria, Iraq/Iran and the Levant are likely sources for the plant ash glasses identified in this study. Plant ash glasses were mass produced in early Islamic cosmopolitan centres such as Damascus, Baghdad and Samarra[411] and started to appear on European sites in any number as a result of Viking trade networks.

In the absence of glass making furnaces in the Netherlands, Belgium and northern France are possible sources of wood ash glass but a more likely source is Germany which formed part of the Viking trade network, including Hedeby in northern Germany. The probable evidence for mixed-alkali glass production in France suggests that this is one possible source for the type of glass in the early medieval Netherlands though again Germany may also have been a source.

vi. To what extent were the raw materials or semi-finished products derived from primary production sites, and to what extent did they derive from systematic recycling of glass, including Roman?

In 'pristine' (non-recycled) natron glass the levels of a few correlated elements such as Pb, Sb and Cu, Ba, Rb, Cs are low or very low, but for recycled glass the levels of these elements are higher. Elevated levels of Pb and Sb most consistently demonstrate recycling has occurred, so they have been chosen here as one of the means of distinguishing 'pristine' glass samples from recycled glass samples. The criterion for the identification of a 'pristine' glass is that the Pb and Sb contents are both under 1000 ppm, following previous conventions.

We have noted that there is a higher proportion of 'pristine' (unrecycled) natron glass imported as a raw material, however indirectly, from primary production sites found on Merovingian sites than on Carolingian sites. For example 'pristine' Foy 2 glasses from the late 6th-early 7th century Maastricht Jodenstraat site were used as the base glass to make highly coloured yellow, white and red opaque glass beads there and perhaps the translucent glass beads too. The same was found for the few semi-finished products from the site. The late 4th to mid 6th century glass vessels analysed from Gennep are pristine HIMT *sensu stricto* or 'pristine' Foy 2 glass. Nevertheless, elevated levels of Sb and Pb suggest there was an admixture of highly coloured Roman vessel glass or glass tesserae to some glass as early as this.

In contrast if we use the results of 55 vessel glasses from Dorestad dating to the Carolingian period we have found that, apart from two wood ash glasses, and an Egyptian II glass, the remaining glasses are of the Foy 2 composition. These Foy 2 glasses contain at least 1000 ppm of Pb or 1000 ppm of Sb, or both, as well as elevated levels of Rb and Cs, characteristics of recycled glasses.

By the *c.* 850 and into the 10th-11th centuries the site of Deventer provides an intriguing contrast to earlier periods, reflecting an important period of technological transition. From the glass that is sufficiently unweathered to provide a valid analysis nineteen out of thirty-eight samples are of a wood ash composition, twelve are natron glass, four are mixed-alkali and one is a plant ash glass. Therefore, wood

[410] Gliozzo *et al.* 2019.
[411] Henderson 2022.

ash and plant ash glasses are unrecycled; the mixed-alkali glasses are the product of recycling. The twelve natron glasses surprisingly include three of a Roman composition, three of a 'pristine' Egyptian II composition, one 'pristine Foy II glass and five recycled Foy 2 glasses. Therefore the majority of glasses analysed from Deventer are pristine and have not been recycled.

It would seem therefore, that the lowest proportion of recycled glass was imported and used in the late 6th-early 7th century and between *c.* 850 and 10th-11th centuries, partly in the latter case because decentralized primary production of wood ash glass had developed. Between these dates there was clearly a dependence on using recycled glass for making the majority of vessels found at Dorestad.

The research also provides building blocks for two NOaA questions:

What are the nature, manifestations, extent and context of craft specialization? (NOaA 2.0 question 67)

The description of glass craft specialization is discussed in detail in Chapter 3, some of which is ephemeral. Therefore only the most significant evidence is discussed here. Monochrome glass bead production was a craft specialization in the early medieval Netherlands. The most comprehensive evidence in Europe to date for the manufacture, especially of opaque yellow glass beads, has been excavated from the Jodenstraat 30 site in Maastricht where a rubbish pit filled with the debris from glass bead making was found.[412] The pit also contained waste from copper-alloy-working and amber-working.[413] Based on the pottery finds, the pit was filled sometime in the late 6th to early 7th centuries. The debris from bead making consists of 750 glass objects which represent the full range of waste from glass bead production. The production waste was divided into eight main groups: glass rods (n=369), 'punty' glass from a beadmaker's tool (n=36), glass threads with and without tweezer marks (n=17), glass drops (n=39), finished and failed beads (n=123), crucibles (n=38, EMN=17), cullet or scrap glass (n=20), glassy slags/fuel ash slags (n=53) and non-diagnostic fragments (n=55) which include (small lumps of) melted glass and fragments that are too small to classify. All waste categories are dominated by opaque yellow glass (apart from scrap glass and glassy slags). Almost all beads are wound and have tapering perforations showing they were made by winding melted glass around a mandrel, a bead-making tool with a conical point. Such a tool may have been found at the Rijksarchief site. The crucibles associated with bead production consist of 38 fragments from at least 17 coarse-ware cooking pots (*Wölbwandtöpfe*). In 15 cases, only the lower halves of the pots were used to melt highly coloured opaque yellow glass. Two crucible bases with opaque white pigment are also present. Drops of translucent greenish glass among the waste products suggest this glass colour was worked on or near the site.

Excavations at the Maastricht Mabro site produced twelve fragments of crucibles with glass deposits; eleven of these date to the 6th-7th centuries. The colours of the glass in the crucibles are colourless or pale green or opaque yellow. A number of wound beads have been found: they are either monochrome or decorated with trails in contrasting colours. The site has not been published, so it is impossible to state which beads are likely to be local products, but given the dates for the crucibles, those beads dating to roughly the 2nd half of the 6th and first half of the 7th century are the most likely candidates: a small globular bead, a bi-globular bead and a possible cylindrical bead of opaque yellow glass, a medium-sized globular bead of opaque white glass and a short cylindrical bead of opaque red glass. There are also two polychrome, trailed beads: an opaque white globular bead with translucent light blue narrow crossing trails and an opaque white disc-shaped bead with translucent dark blue crossing trails.

Excavations of the Maastricht-Rijksarchief site are discussed by Hulst.[414] Dozens of rubbish pits were full of the evidence for glass working, antler working and iron working and dated by (late) 5th and 6th century pottery. The evidence of glass working consists of 55 fragments of early Merovingian vessel glass, two fragments of glass rods, 25 beads, drops of glass, melted glass, glassy slags and fragment of a glass crucible.[415] Furthermore, one fragment of a glass crucible, glassy slags (included some attached to a furnace floor or thick tray fragment) were found. A forged iron rod which is round in section at one end and square in section at the other match the perforations of beads found on the site; it is an example of a very unusual bead-

[412] Sablerolles, Henderson & Dijkman 1997.
[413] For waste from amber-working, see Dijkman 2013.
[414] Hulst 1992.
[415] Hulst 1992.

making mandrel around which glass filaments would have been wound.

Evidence for the manufacture of opaque yellow glass was also found at Wynaldum in the form of a thick fragment covered with a layer of opaque yellow material of between 1.0-1.3 cm thick. The yellow substance would probably have been used to make beads once formed into glass. Two small flattened opaque yellow and white beads were found and are probably local products. This evidence was found amongst waste produced by a blacksmith/bronze-caster. The dump dates to the last quarter of the 6th and the first quarter of the 7th century and is contemporary with the glass-working evidence from the Jodenstraat site in Maastricht. A tessera and a piece of punty glass glass were found in Carolingian contexts. There is a possibility that they relate to bead production.

Brightly coloured Merovingian monochrome beads would presumably have been used by local populations but would also have been exported. As mentioned in Chapter 6 there was evidently a demand especially for bright yellow glass beads from at least the middle Merovingian period; such glass must have had social significance but it is difficult to suggest what it might have been.

The five fragments of glass production waste have been found at the monastic site of Susteren-Abdijterrein suggest that glass was worked there during the early medieval period.[416] The finds are two fragments of glass crucibles (one with a layer of cobalt blue glass and the other with a layer of bluish green and colourless glass attached), a partially melted Roman tessera, a glass fragment from glassblowing tool and a possible fragment of opaque yellow raw glass. The crucible fragments derive from a context dated to 800–1300 which contains 60% redeposited Carolingian material. One crucible fragment, which contains bluish-green glass, is probably made of Carolingian Badorf ware.[417] The second crucible fragment which contains cobalt blue blue glass was made of possible grey Meuse Valley ware: it may have been used to make dark blue window quarries on the site, the first such evidence from the Netherlands. A partially melted, opaque dark blue Roman tessera may have formed part of the manufacture. A translucent dark bluish-green glass fragment with thick walls is covered on its concave inside with dark grey iron scale from a glassblowing tool. This fragment is the only direct evidence for glassblowing in the Netherlands since the Roman period.

Excavations at Wijk bij Duurstede-Veilingterrein and Frankenweg/Zandweg revealed evidence for Carolingian bone- working (and those at the adjoining Parkeerplaats Albert Heijn (PPAH) site produced traces of metal working and loom weights).[418] Some thirty-six fragments of glass-working waste were found, including eight tesserae, a large fragment of a glass crucible of a late Merovingian form found in a pit with two blue tesserae, a regular and an irregular drop of translucent pale green glass, a small dark sphere, six melted lumps of translucent pale green vessel glass and a melted fragment of 'black', deep olive-green glass. The crucible contains almost colourless glass of *c.* 1 mm thickness with a thicker patch of opaque white glass which is probably a melted tessera. Preiß points out that defects in the translucent glass probably indicate locations where other (crushed?) tesserae had been attached.[419] The crucible may be linked to bead-making, but it also may be linked to vessel or window glass production at the site.

Excavations at Wijk bij Duurstede – Veilingterrein and Frankenweg/Zandweg revealed evidence for glass production along with iron smithing, brass production, weaving (wool) and amber working; glass and amber working evidence were sometimes found in close proximity. The largest category of glass working evidence is tesserae, almost all a blue/green colour. Fragments of translucent bluish-green and dark blue glass probably result from breaking up glass ingots, cakes or raw glass chunks. There are dark blue drops, two square sectioned opaque yellow glass rods and opaque white glass which were probably used for bead-making. A lump of opaque yellow glass has part of a composite opaque yellow glass rod and yellow punty glass from a glassworker's tool melted onto it. An opaque green object is waste from glass bead production; there is also a twisted bi-chrome (opaque white and blue-green) rod fragment. Such rods were used or decorating Carolingian glass vessels. A thick opaque yellow glass fragment has embedded iron oxide scale in it as well as ceramic fragments. It may have been used in bead production or decorating 8th century vessels. A 'bright blue' tessera and clay covered with a thick layer of 'blobby greenish glass' were found on the

416 Sablerolles 2023. (basispublicatie chapter 29).
417 Pottery identification by Jan de Koning.
418 Nyst 2003, 13.
419 Preiß 2010, 125.

Veilingterrein site.[420] Moreover two small spheres of whitish translucent glass were found.[421]

The finds from Dorestad therefore provide evidence for local bead production; vessels may also have been made there. The relatively small amount of glass production debris derives from pits, wells and ditches; wet sieving was not carried out universally. It is therefore difficult to decide whether the evidence indicates that production was on a small-scale, at household level, or on a larger scale for export.

Excavations at Utrecht Domplein produced twelve crucible fragments with a layer of glass attached to their insides. The glass is either apparently colourless, green with red streaks of glass running through it or pale green. Red marbled translucent blue-green/bluish-green glass was popular for making late Merovingian and Carolingian glass vessels. Excavations at Utrecht Oudwijkerdwarsstraat produced an irregular drop of bluish-green glass as well as some crushed fragments. The discovery of fourteen hundred amber fragments shows that some craft activity occurred on quite a large scale.

The evidence from Merovingian Leidsche Rijn-Leeuwesteyn Noord consists of a single crucible fragment with a layer of blue-green glass with marbled opaque red streaks perhaps used to make windows. The Merovingian Rijnsburg-Abdijterrein site produced some useful evidence for glass bead production consisting of finished, unfinished and failed beads, glass rods and three pieces of punty glass from a beadmaker's tool; eight crucible fragments and two lumps of fired clay covered with translucent greenish glass could have been part of a glass-working furnace floor. A single crucible fragment with green glass attached may be contemporary. Nearly half of the waste from Rijnsburg is opaque yellow. The crucible fragments have yellow and colourless glass attached to them. This material was not available for this research project. It is possible that colourless glass was modified on site using lead-tin yellow. The chemical composition of the yellow glass in the crucible, the beads and the rods are similar and therefore likely to have been made on site. The bead types made at Rijnsburg were monochrome opaque yellow globular, bi- and tri-globular beads and bi-globular red beads. Trailed beads include bi-globular beads of red glass with both white crossing trails and a white spiral, tri-globular beads of opaque red glass with opaque white crossing trails and white beads with translucent blue crossing trails were also possibly made at the site. It is likely that the production phase occurred in the 7th century partly based on dated bead typologies (see Section 3.8).

Two hundred and one (unstratified) glass tesserae from the terp at Wierum have been interpreted as a supply of 'raw' glass for making beads in the early medieval period.[422] The terp probably dates to the 8th/9th centuries. Most tesserae have rounded profiles so appear to have been heated. Five fragments of highly coloured early Roman vessel glass, one fragment of Roman or early medieval vessel glass, three opaque green nearly colourless and translucent dark blue plano-convex drops of glass and thirteen irregular drops/melted lumps of nearly colourless, pale green and pale blue-green glass have also been found. This evidence from Wierum may have resulted from a travelling beadmaker visiting terp sites such as Wijnaldum in the northern coastal region, which was most easily accessible by boat from the central riverine area, with Dorestad at its centre.

The latest site to be considered in our research project is Deventer- Stadhuiskwartier. The evidence for the glass industry is scanty, dates to between *c.* 850 and *c.* 1050 and derives from waste pits or cesspits. Two pits yielded production waste of iron smithing, bone-working and textile production; glassy slag dates to 850–900. Glass working evidence dating to between 900 and 925 consists of a heavily weathered chip of glass with a conchoidal fracture, a heavily weathered triangular fragment and a small, heat-affected fragment which may be part of a pulled thread. Waste from the 900–950 phase consist of a small lump of translucent clear bluish-green raw glass, a heavily weathered fragment with a triangular section and a heavily weathered fragment with two irregular, heat-affected surfaces. An unusual fragment dating to 950-1050 consists of a translucent bright bluish-green and deep turquoise glass layer covered by a very thin film of opaque red glass. The turquoise colour is very similar to a contemporary fragment of very thin flat glass, either window glass or a glass inlay, found in the same area.

It is evident that early medieval glass working in the Netherlands was frequently

[420] Van Doesburg 2004.
[421] Langbroek 2021b, 64, table 7, findnrs Zandweg WD 754.2.63b, WD 754.2.63b.
[422] Crocco *et al.* 2021.

associated in industrial areas on the sites with a range of other industries including iron smithing, copper-alloy production and brass production, as well as amber working and weaving. It is likely that the same fuels (yet to be determined) would have been used for glass and metal production, depending on the maximum temperature required. The artisans involved in glass working may have taken part in other activities associated with shared aspects of other high temperature industries, such as obtaining fuel, making crucibles and building kilns/furnaces or separate groups were involved in such activities.
During the Carolingian period such industrial organisations, that were involved in several different production activities on particular sites, have been found, for example, at San Vincenzo al Voltorno, Augsburg and Corvey.[423]

[423] Verhulst 2002, 72-84.

Where do non-local raw materials of utilitarian objects come from? (NOaA 2.0 question 139)
There is evidence that much of the base glass used to make utilitarian beads and vessels originated in Egypt; by the Carolingian period most of it was recycled to the extent that its source is indeterminate but most still has evidence that the ultimate source of almost all 'pristine' unrecycled glass was Egypt. The small number of plant ash glasses used to make utilitarian objects in the early medieval Netherlands probably derived from Iraq/Iran, Syria and the Levant. The lead and perhaps the cobalt may have originated in Germany, but this is to be confirmed - and there are other possible sources. The possible sources of tin are more restricted: Cornwall in the UK is one such source; Turkey is another one.

Bibliography

Adlington, L.W., I.C. Freestone, J.J. Kunicki-Goldfinger, T. Ayers, H. Gilderdale Scott & A. Eavis 2019: Regional patterns in medieval European glass composition as a provenancing tool, *Journal of Archaeological Science*, 110, 104991.

Aldsworth, F., G. Haggerty, S. Jennings & D. Whitehouse 2002: Medieval Glassmaking at Tyre, Lebanon, *Journal of Glass Studies* 44: 49–66.

Alfonsi, H. & Gandolfo P. 1997: L'épave Sanguinaire A, *Cahiers d'Archéologie subaquatique* 13, 35-74.

Allan, J.W., 1973: Abū'l-Qāsim's treatise on ceramics, *Iran*, 11, 111–120.

Andersen, J.H. & T. Sode 2010: The Glass Bead Material, in: M. Bencard & H.B. Madsen (eds), *Ribe Excavations 1970–76, vol. 6.*, Ribe Esbjerg: Sydjysk Universitetsforlag (Ribe Excavations, Jutland Archaeological Society Publications), 17–59.

Arbman, H., 1937: *Schweden und das Karolingische Reich. Studien zu den Handelsverbindungen des 9. Jahrhunderts. Kungl, Stockholm (Vitterhets Historie och Antikvitets Akademiens Handlingar Del 43).*

Ares, J.D.J., A.V.E. Guirado, Y.C. Gutiérrez & N. Schibille 2019: Changes in the supply of eastern Mediterranean glasses to Visigothic Spain, *Journal of Archaeological Science*, 107, 23–31.

Artioli, G., C. Canovaro, P. Nimis & I. Angelini 2020: LIA of Prehistoric Metals in the Central Mediterranean Area: A Review, *Archaeometry*, 62, 53-85.

Aunay, C., A.A. Berthon, B. Gratuze, M. Guérit, J. Motteau & I. Pactat 2020: Le verre creux du VIIIe au Xe siècle dans la vallée de la Loire moyenne et de la Vienne. Essai typo-chronologique et archéométrique, in: Inès Pactat & C. Munier (eds), *Le verre du VIIIe au XVIe siècle en Europe occidentale*, Les Cahiers de la MSHE Ledoux, Presses universitaires de Franche-Comté, 293–314.

Bandiera, M., M. Verità, P. Lehuédé & M. Vilarigues 2020: The technology of copper-based red glass sectilia from the 2nd century AD Lucius Verus villa in Rome, *Minerals*, 10(10), 875.

Barber, D.J, I. Freestone & K.M. Moulding 2009: Ancient Copper Red Glasses: investigation and analysis by microbeam techniques, Chapter 11 in: A.J. Shortland, I.C. Freestone & T. Rehren (eds), *Mine to Microscope*, Oxford: Oxbow Books & the David Brown Book Company.

Bardet, A.C., 1995: Pottery traded to Dorestad: some explanatory archaeometrical analyses of early medieval Rhenish wares, *Berichten van de Rijksdienst voor Oudheidkundig Bodemonderzoek*, 41, 187–251.

Bass, G.F., 1984: The nature of the Serçe Limani glass, *Journal of Glass Studies* 26, 64–9.

Bass, G.F., B. Lledo, S. Matthews & R.H. Brill 2009: *Serçe Limani. Volume 2: The glass of an eleventh-century shipwreck*, Rachel Foundation Nautical Archaeology Series, College Station, Texas A & M University Press.

Baumgartner, E. & I. Krüger 1988: *Phoenix aus Sand und Asche. Glas des Mittelalters*, München.

Bertini, C., J. Henderson & S. Chenery 2020: Seventh to eleventh century CE glass from Northern Italy: between continuity and innovation, *Archaeological and Anthropological Sciences*, 12:120. https://doi.org/10.1007/s12520-020-01048-8

Besteman, J.C., J.M. Bos, D.A. Gerrets, H.A. Heidinga & J. de Koning (eds) 1999: *The Excavations at Wijnaldum. Reports on Frisia in Roman and Medieval times*, Volume I, Rotterdam/Brookfield.

Birck, J.L., 1986: Precision of K-Rb-Sr Isotopic Analysis - Application to Rb-Sr Chronology, *Chemical Geology*, 56, 73-83.

Boschetti, C., J. Henderson, J. Evans & C. Leonelli 2016: Mosaic tesserae from Italy and the production of Mediterranean coloured glass (4th century BC–4th century AD). Part I: Chemical composition and technology, *Journal of Archaeological Science*, Reports, 7, 303–311.

Boschetti, C., C. Leonelli, R. Rosa, M. Romagnoli, M. Valero Tévar & N. Schibille 2020: Antimony or Opacified White Glass Tesserae, *Heritage*, 3, 549–560. https://doi.org/10.3390/heritage3020032

Boschetti, C., B. Gratuze & N. Schibille 2020: Commercial and social significance of glass beads in Migration-Period Italy: the cemetery of Campo Marchione, *Oxford Journal of Archaeology*, 39, issue 3, 319–342.

Brems, D., M. Ganio, K. Latruwe, L. Balcaen, M. Carremans, D. Gimeno, A. Silvestri, F. Vanhaecke, P. Muchez & P. Degryse 2013a: Isotopes on the beach, part 1: strontium isotope ratios as a provenance indicator for lime raw materials used in Roman glass-making, *Archaeometry* 55, 214-234.

Brems, D., M. Ganio, K. Latruwe, L. Balcaen, M. Carremans, D. Gimeno, A. Silvestri, F. Vanhaecke, P. Muchez, & P. Degryse 2013b: Isotopes on the beach, part 2: neodymium isotopic analysis for the provenancing of Roman glass-making, *Archaeometry*, 449-464.

Brems, D., I.C. Freestone, Y. Gorin-Rosen, R. Scott, V. Devulder, F. Vanhaecke & P. Degryse 2018: Characterisation of Byzantine and early Islamic primary tank furnace glass, *Journal of Archaeological Science: Reports*, 20, 722–735.

Brill, R.H., 2005: Chemical Analyses of Some Sasanian Glasses from Iraq, in: David Whitehouse, *Sasanian and Post Sasanian Glass in The Corning Museum of Glass*, Corning: the museum, 2005, 65–88.

Brill, R.H., 2006: Scientific Investigations of Some Glasses from Jarrow and Monkwearmouth, in: R. Cramp, *Wearmouth and Jarrow monastic sites*, volume 2, English Heritage.

Brüggler, M., 1994: Burgus und Glaswerkstatt der Spätantike bei Goch-Asperden, *Berichte. Grabung–Forschung–Präsentation*, Köln.

Bult, E.J., J. van Doesburg & D.P. Hallewas 1990: De opgravingscampagne in de Vroeg-Middeleeuwse nederzetting op de Woerd bij Valkenburg (Z.H.) in 1987 en 1988, in: E.J. Bult & D.P. Hallewas (eds), *Graven bij Valkenburg III, het archeologisch onderzoek in 1987 en 1988*, Delft, 147–166.

Cabart, H., I. Pactat & B. Gratuze 2017: Les verres du Haut Moyen âge issus des fouilles du monasterium Habendum (Vosges, France), *Annales du 20e Congrès de l'Association Internationale pour l'Histoire du verre*, 346–353.

Cagno, S., M.B. Badano, F. Mathis, D. Strivay & K. Janssens 2012: Study of medieval glass fragments from Savona (Italy) and their relation with the glass produced in Altare, *Journal of Archaeological Science*, 39 (7), 2191–2197.

Callmer J., 1977: *Trade beads and bead trade in Scandinavia ca. 800–1000 AD*, Acta Archaeologica Lundensia, 4 , 11, Habelt, Bonn.

Callmer, J., 2003: Wayland. An essay on craft production in the Early and High Middle Ages in Scandinavia, in: L. Larsson & B. Hårdh (eds), *Centrality-Regionality: the social structure of southern Sweden during the Iron Age*, Stockholm. Acta Arch. Ludensia Ser. 8°, 40, 337-361.

Callmer, J. & J. Henderson 1991: Glassworking at Åhus, S. Sweden (eighth century AD), *Laborativ Arkeologi*, 5, 143–154.

Casellato, U., F. Fenzi, P. Guerriero, S. Sitran, P.A. Vigato, U. Russo, M. Galgani, M. Mendera & A Manasse 2003: Medieval and renaissance glass technology in Valdelsa (Florence). Part 1: raw materials, sands and non-vitreous finds, *Journal of Cultural Heritage*, 4, (4), 337-353.

Ceglia, Andrea, P. Cosyns, K. Nys, H. Terryn, H. Thienpont & W. Meulebroeck 2015: Late antique glass distribution and consumption in Cyprus: a chemical study, *Journal of Archaeological Science*, 61, 213–222.

Ceglia, Andrea, P. Cosyns, N. Schibille & W. Meulebroeck 2019: Unravelling provenance and recycling of Late Antique glass with trace elements, *Archaeological and Anthropological Sciences*, 11, 279–291.

Conte, S., T. Chinni, R. Arletti & M. Vandini 2014: Butrint (Albania) between eastern and western Mediterranean glass production: EMPA and LA-ICP-MS of late antique and early medieval finds, *Journal of Archaeological Science*, 49, 6–20.

Corbella, F., 2017: *The Lent Merovingian glass beads µ-Computed Tomography, XRF and SEM analysis of complex glass beads*, Unpublished Internship report at TU Delft for École Polytechnique, Université Paris-Saclay, s.l., s.n., 64 pp.

Crocco, R., H. Huisman, Y. Sablerolles, J. Henderson, B. van Os & A. Nieuwhof 2021: Hunting colours: origin and reuse of glass tesserae from the Wierum terp, *Archaeological and Anthropological Sciences*, 13(9), 1–22. https://doi.org/10.1007/s12520-021-01391-4

De Bruin, J., 2018: Living in Oegstgeest 575–725 AD, in: M. Kars, R. van Oosten, M.A. Roxburgh & A. Verhoeven, *Rural riches & royal rags? Studies on medieval and modern archaeology, presented to Frans Theuws*, Zwolle: SPA-Uitgevers, 20–25.

De Bruin, J., C. Bakels & F. Theuws (eds) 2021: *Oegstgeest. A riverine settlement in the early medieval world system*, Bonn: Habelt Verlag.

De Koning, J., 2012: Het aardewerk, in: J. Dijkstra (ed.), *Het domein van de boer en de ambachtsman. Een opgraving op het terrein van de voormalige fruitveiling te Wijk bij Duurstede: een deel van Dorestad en de villa Wijk archeologisch onderzocht*, ADC monografie 12, Amersfoort, 117–235.

De Koning, J., 2015: *Onder het stuifzand. Overstoven vroeg-middeleeuwse nederzettingen bij Bloemendaal de opgravings-campagnes Groot Olmen 2005: 2006 en 2007*, Zaandijk.

De Sigoyer, S.D.B., C. Peters, S. Mathieu & C. Fontaine 2005: Vestiges de fours de verriers d'epoque Mérovingien à Huy aux Ruelles (Belgique): Aperçu des trouvailles, *Bulletin de l'Association Française pour l'Archéologie du Verre*, 2005, 29–33.

Degryse, P. & J. Schneider 2008: Pliny the Elder and Sr–Nd isotopes: tracing the provenance of raw materials for Roman glass production, *Journal of Archaeological Science*, 35(7), 1993–2000.

Degryse, P., I. Freestone, S. Jennings & J. Schneider 2010: *Technology and provenance study of Levantine plant ash glass using Sr–Nd isotope analysis*, Römisch-Germanisches Zentralmuseum.

Dekówna, M., 1978: Les verres de Haithabu. Rapport préliminaire, *Annales du 7e Congrès de l'Association Internationale pour l'Histoire du Verre, Liège*, 167-188.

Dekówna, M., 1980: Methods of examining ancient glasses, in: J. Schild (ed.), *Unconventional Archaeology*, Wroclaw: Ossolineium, Wydawnictwo Polskiej Akademii Nauk, 213–233.

Dell'Acqua, F., 1997: Ninth-century window glass from the monastery of San Vincenzo al Volturno (Molise, Italy), *Journal of glass studies*, 33–41.

DePaolo, D.J. & G.J. Wasserburg 1976: Nd isotopic variations and petrogenetic models, *Geophysical Research Letters*, 3(5), 249–252.

Dijkman, W., 2013: Artisanal Activities in Merovingian Maastricht, *Medieval and Modern Matters*, 4, 23–39.

Dijkstra, J. (ed.) 2012: *Het domein van de boer en de ambachtsman. Een opgraving op het terrein van de voormalige fruitveiling te Wijk bij Duurstede: een deel van Dorestad en de villa Wijk archeologisch onderzocht*, Amersfoort (ADC-monografie 12).

Dijkstra, M.P.F. 2011: Rondom de mondingen van de Rijn en Maas. Landschap en bewoning tussen de 3e en de 9e eeuw in Zuid-Holland, in het bijzonder de Oude Rijnstreek, (PhD thesis University of Amsterdam).

Dijkstra, M., Y. Sablerolles & J. Henderson 2011: A traveller's tale. Merovingian glass bead production at Rijnsburg, the Netherlands, in: C. Theune, F. Biermann, R. Struwe & G.H. Jeute, *Zwischen Fjorde und Steppe, Festschrift für Johann Callmer zum 65. Geburtstag*, Rahden/Westf.: Leidorf, 175–199 (Internationale Archäologie; Studia honoraria; Band 31).

Dodt, M., A. Kronz & K. Simon 2021: Production of early medieval glass in Cologne, in: A. Willemsen and H. Kik (eds), *Dorestad and its networks*, Proceedings of the third 'Dorestad Congress' held at the National Museum of Antiquities, Leiden, the Netherlands 12–15 June 2019, 179–191.

Evison, V.I., 1972: Glass Cone Beakers of the "Kempston" Type, *Journal of Glass Studies*, 48–66.

Fontaine, S. D. & D. Foy 2007: L' épave Ouest-Embiez 1, Var; le commerce maritime du verre brut et manufacturé en Méditerranée occidentale dans l'Antiquité, *Revue Archéologique de Narbonnaise*, 40, 235-268.

Foster, H.E. & C.M. Jackson 2009: The composition of 'naturally coloured' late Roman vessel glass from Britain and the implications for models of glass production and supply, *Journal of Archaeological Science*, 36(2), 189–204.

Foy, D. & M.-D. Nenna 2001: *Tout feu tout sable: mille ans de verre antique dans le Midi de la France*, Edisud, Marseilles.

Foy, D., M. Picon, M. Vichy & V. Thirion-Merle 2003: Caractérisation des verres de la fin de l'Antiquité en Méditerranée Occidentale: l'émergence de nouveaux courants commerciaux, in: D. Foy & M.-D. Nenna (eds), Échanges et commerce du verre dans le monde antique, Actes du colloque de l'Association française pour l'archéologie du verre, Aix-en-Provence, juin 2001, 41–85, Éditions Monique Mergoil, Montagnac.

Freestone, I.C., 2015: The recycling and reuse of Roman glass: analytical approaches, *Journal of glass studies*, 29–40.

Freestone, I.C., Y. Gorin-Rosen & M.J. Hughes 2000: Primary glass from Israel and the production of glass in late antiquity and the early islamic period, in: N. Marie-Dominique (ed.), *La route du verre. Ateliers primaires et secondaires du second millénaire av. J.-C. au Moyen Âge*, Maison de l'Orient et de la Méditerranée, Jean Pouilloux, Lyon, 65–83.

Freestone, I.C. & M.J. Hughes 2006: The origins of Jarrow glass, in: R. Cramp, *Wearmouth and Jarrow Monastic sites*, Vol. 2, English Heritage, 147–155.

Freestone, I.C., R.E. Jackson-Tal, O. Tal & I. Taxel 2015: Glass production at an early Islamic workshop in Tel Aviv, *Journal of Archaeological Science* 62, 45-54.

Freestone, I.C., P. Degryse, J. Lankton, B. Gratuze & J. Schneider 2018: HIMT, glass composition and commodity branding in the primary glass industry, in: D. Rosenow, M. Phelps, A. Meek & I. Freestone (eds), *Things that Travelled: Mediterranean Glass in the First Millennium AD*, UCL Press, 159–190. https://doi.org/10.2307/j.ctt21c4tb3.14

Gai, S., 2005: Vitres et vitraux du palais impérial de Charlemagne à Paderborn, in: D. Foy (ed.), *De transparentes spéculations. Vitres de l'Antiquité et du haut Moyen Âge (Occident-Orient)*, Exposition temporaire en liaison avec les 20e rencontres de l'AFAV sur le thème du verre plat, Bavay, Musée-site d'archéologie, 83–85.

Gallo, F., A. Silvestri, P. Degryse, M. Ganio, A. Longinelli & G. Molin 2015: Roman and late-Roman glass from north-eastern Italy: The isotopic perspective to provenance its raw materials, *Journal of Archaeological Science*, 62, 55–65.

Gam, T., 1990: Prehistoric Glass Technology – Experiments and Analyses, *Journal of Danish Archaeology*, 9, 203–213.

Ganio, M., M. Gulmini, K. Latruwe, F. Vanhaecke & P. Degryse 2013: Sasanian glass from Veh Ardašīr investigated by strontium and neodymium isotopic analysis, *Journal of archaeological science*, 40(12), 4264–4270.

Gaut, B., 2011: Vessel Glass and Evidence of Glassworking in Skre, D. (ed.). *Things from the town: artefacts and inhabitants in Viking-age Kaupang*, Kaupang Excavation Project publication series volume 3, Aahus University Press, 169-258.

Gaut, B. & J. Henderson 2011: Compositional analysis. Appendix 9.1 in Skre, D. (ed.). *Things from the town: artefacts and inhabitants in Viking-age Kaupang*, Kaupang Excavation Project publication series volume 3, Aahus University Press, 262-271.

Genga, N., M. Siciliano, A. Tepore, A. Mangone, A. Traini & C. Laganara 2008: An archaeometric approach about the study of medieval glass from Siponto (Foggia, Italy), *Microchemical Journal*, 90, (1), 56-62.

Gliozzo, E., E. Braschi, F. Giannetti, A. Langone & M. Turchiano 2019: New geochemical and isotopic insights into the Late Antique Apulian glass and the HIMT1 and HIMT2 glass productions—the glass vessels from San Giusto (Foggia, Italy) and the diagrams for provenance studies, *Archaeological and Anthropological Sciences*, 11, 141–170.

Gorin-Rosen Y., 2000: The ancient glass industry in Israel—summary of the finds and new discoveries, in: M.-D. Nenna (ed.), *La route du verre Ateliers primaires et secondaires du second millénaire av. J.C. au Moyen Âge*, Maison de l'Orient Méditerranéen, Jean Pouilloux, Lyon, 49–63.

Gratuze, B. & J.-N. Barrandon 1990: Islamic glass weights and stamps, *Archaeometry*, 32, 155–162.

Gratuze, B., D. Foy, J. Lancelot & F. Téreygeol 2003: Les “lissoirs” carolingiens en verre au plomb: mise en evidence de la valorisation des scories issues du traitement des galènes argentifères de Melle (Deux-Sèvres), in: D. Foy & M.-D. Nenna (eds), *Échanges et commerce du verre dans le monde antique*, Actes du colloque de l'AFAV, Aix-en-Provence et Marseille, 7–9 June 2001, Montagnac, France: Éditions Monique Mergoil, 101–108.

Haevernick, T.E., 1979: Karolingisches Glas aus St Dionysius in Esslingen, *Forschungen und Berichte der Archäologie des Mittelalters in Baden-Württemberg*, 6, 157–171.

Heaser, S., 2018: *Anglo-Saxon Glass Beadmakers*, s.l. 19 pp.

Heck, M., T. Rehren & P. Hoffmann 2003: The production of lead–tin yellow at Merovingian Schleitheim (Switzerland), *Archaeometry*, 45(1), 33–44.

Hemminga, M. & T. Hamburg 2006: *Een Merovingische nederzetting op de oever van de Oude Rijn. Opgraving (DO) en Inventariserend Veldonderzoek (IVO) Oegstgeest - Rijnfront zuid 2004*, Leiden (Archol Rapport 69).

Hemminga, M., T. Hamburg, M. Dijkstra, C. Cavallo, S. Knippenberg, S.M.E. van Lith, C.C. Bakels & C. Vermeeren 2008: *Vroegmiddeleeuwse nederzettingssporen te Oegstgeest. Een Inventariserend Veldonderzoek en Opgraving langs de Oude Rijn*, Leiden (Archol Rapport 102).

Henderson, J., 1985: The raw materials of early glass production, *Oxford Journal of Archaeology*, 4(3), 267–291.

Henderson, J., 1985: The raw materials of early glass production, *Oxford Journal of Archaeology*, *4*, 267-291.

Henderson, J., 1989: The scientific analysis of ancient glass and its archaeological interpretation, in: J. Henderson (ed.), *Scientific analysis in archaeology and its interpretation*, Oxford University Committee on Archaeology Monograph no. 19, UCLA Institute of Archaeology Research Tools 5, Oxford: Oxbow Books, 30–62.

Henderson, J., 1991a: Chemical characterisation of Roman glass vessels, enamels and tesserae, in: P.B. Vandiver, J. Druzik & G.S. Wheeler (eds), *Materials issues in art and archaeology II*, Research Society Symposium Proceedings, vol. 185, Pittsburgh, PA: Materials Research Society, 601–607.

Henderson, J., 1991b: The glass, in: P. Armstrong, D. Tomlinson & D.H. Evans (eds), *Excavations at Lurk Lane Beverley 1979–82*, Sheffield Excavation Reports 1, Sheffield, England: J.R. Collis, 124–30.

Henderson, J., 1993: Aspects of Early Medieval glass production in Britain, *Annales du 12e Congrès de l'Association Internationale pour l'Histoire du verre*, Vienna 26–31 August 1991, Amsterdam: AIHV, 247–259.

Henderson, J., 1999: Scientific analysis of the glass and glass-bearing artefacts: Technique, raw materials used and archaeological interpretation, in: J.C. Besteman, J.M. Bos, D.A. Gerrets, H.A. Heidinga & J. de Koning, *The Excavations at Wijnaldum, reports on Frisia in Roman and Medieval times, volume 1*, Rotterdam: Balkema, 287–297.

Henderson, J., 2000: *The science and archaeology of materials*, Routledge: London and New York.

Henderson, J., 2002: Tradition and experiment in 1st millennium ad glass production – the emergence of early Islamic glass technology in late antiquity, *Accounts of Chemical Research*, 35, 594–602.

Henderson, J., 2012: De Glasvondsten, in: *Het domain van de boer en de ambachtsman. Een opgraving op het terrein van de voormalige fruitveiling, te Wijk bij Duurstede: een deel van Dorestad en de villa Wijk archeologisch onderzocht*, Amersfoort (ADC Monografie 12), 293–354.

Henderson, J., 2013: *Ancient glass, an interdisciplinary exploration*, New York and Cambridge: Cambridge University Press.

Henderson, J., 2022: The politics of production, glass provenance and social context on the early Islamic Silk Roads, *Journal of Islamic Archaeology* 8.2, 203-237.

Henderson, J., 2023: Susteren glass: scientific evidence for raw material use, supply and provenance, Stoepker, H. (ed.), 2023: *Sporen van Susteren, archeologische vondsten uit een Karolingisch klooster en een adellijk vrouwenstift, de basispublicatie*, Venlo, 1357-1382. https://doi.org/10.17026/dans-xsf-nypw

Henderson, J., K. Challis, S. O'Hara, S. McLoughlin, S. Gardner & G. Priestnall 2005a: Experiment and innovation: early Islamic industry at al-Raqqa, Syria, *Antiquity*, 79, 1–15.

Henderson, J., J.A. Evans, H.J. Sloane, M.J. Leng, & C. Doherty 2005b: The use of oxygen, strontium and lead isotopes to provenance ancient glasses in the Middle East, *Journal of Archaeological Science*, 32, 665-673.

Henderson, J., S. Chenery, E. Faber & J. Kröger 2016: The use of Electron Probe Microanalysis and Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry for the investigation of 8th–14th century plant ash glasses from the Middle East, *Microchemical Journal*, 128, 134–152.

Henderson J., S. Chenery, E.W. Faber & J. Kröger 2021: Political and technological changes, glass provenance and a new glass production model along the west Asian Silk Road, in: Florian Klimscha (ed.), *Berlin Studies of the Ancient World*, 67, Berlin: edition Topoi.

Henderson, J. & I. Holand 1992: The Glass from Borg, an early Medieval Chieftain's Farm in Northern Norway, *Medieval Archaeology*, XXXVI, 39–58.

Henderson, J. & R. Ivens 1992: Dunmisk and glass-making in Early Christian Ireland, *Antiquity*, 66, 52–64.

Henderson, J., J. Evans & Y. Barkoudah 2009: The roots of provenance: glass, plants and isotopes in the Islamic Middle East, *Antiquity*, 83, 414–429.

Henderson, J., H. Ma & J. Evans 2020: Glass production for the Silk Road? Provenance and trade of Islamic glasses using isotopic and chemical analyses in a geological context, *Journal of Archaeological Science*, 119, 105–164. doi.org/10.1016/j.jas.2020:105164

Henderson, J. & Y. Sablerolles 2020: An overview of Dutch Early Medieval glassworking, published chemical and isotopic analyses of glass beads and vessels, raw, material provenance of beads and vessels, changes in raw material use over time and a plan for future scientific research.

Henderson, J., T. Sode & Y. Sablerolles 2019: Early medieval tesserae from Scandinavia and the Netherlands: a case for re-use and recycling, in: L. Van Wersch, L. Verslype, S. Strivay & F. Theuws (eds), *Early medieval tesserae in Northwestern Europe*, Habelt, Bonn, 68–95.

Henton, A., 2020: Aux portes de l'abbaye d'Elnone – Saint-Amand. Premiers résultats de la fouille préventive de la Grand-Place de Saint-Amand-les-Eaux (Nord, Hauts-de-France), *43e Colloque Archaeologia Mediaevalis*, Mars 2020: Namur, Belgique, 54–58. hal-03229653

Huisman, D.J., J. Van der Laan, G.R.Davies, J.H.van Os, N. Roymans, B.Fermin & M. Karwowski 2017: Purple haze: Combined geochemical and Pb-Sr isotope constraints on colourants in Celtic glass, Journal of Archaeological Science 81, 59-78

Huisman, H., M. Aarts, M. Kars, F. Mulder, D. Ngan-Tillard & B. van Os, 2019, Maken en handelen: Merovingische kralen uit het Sittard-Kemperkoul grafveld geanalyseerd, *Paleoaktueel* 30: 65-74

Hulst, R.A., 1992: Opgravingen Rijksarchief te Maastricht: Merovingische afvalkuilen en laat-middeleeuwse verdedigingswerken, *Archeologie in Limburg*, 42, 89–94.

Isings, C., 1957: *Roman glass from dated finds*, Groningen: Archaeologica Traiectina, 2.

Isings, C., 1978: Glas, *Spiegel Historiael*, 13, 4 (Dorestad-nummer), 260–262.

Isings, C., 2009: Glas, in: M. Nokkert, A.C. Aarts & H.L. Wynia (eds), *Vroeg-middeleeuwse bewoning langs de A2. Een nederzetting uit de zevende en achtste eeuw in Leidsche Rijn*, Utrecht (Basisrapportage Archeologie 26 Gemeente Utrecht), 246–251.

Isings, C., 2015: Glass, in: W.A. van Es & W.J.H. Verwers, *Excavations at Dorestad 4, The settlement on the river Bank Area*, Amersfoort: Nederlandse Oudheden 18, 422–446.

Isings, C., G. Rauws, H. Lägers & R. de Kam 2009: *Schitterend! Twintig eeuwen glas uit Utrechtse bodem*, Utrecht.

Jackson, C.M., C.A. Booth & J.W. Smedley 2005: Glass by design? Raw materials, recipes and compositional data, *Archaeometry*, 47: 781–95.

Jankowiak, M., 2021: Dirham flows into northern and eastern Europe and the rhythms of the slave trade with the Islamic world, in: J. Gruszczyński, M. Jankowiak & J. Shepard (eds), *Viking-Age Trade: Silver, Slaves and Gotland*, Routledge: Abingdon and New York. https://doi.org/10.4324/9781315231808

Jezeer, W. & S. Jongma 2002: *Valkenburg-De Woerd. Werkput 510 – De Geul. Een studie naar vroegmiddeleeuws aardewerk uit Valkenburg (ZH)*, Amsterdam (unpublished thesis, University of Amsterdam).

Kamber, B.S., A. Greig & K.D. Collerson 2005: A new estimate for the composition of weathered young upper continental crust from alluvial sediments, Queensland, Australia, *Geochimica et Cosmochimica Acta*, 69(4), 1041–1058.

Kaspers, A., 2020: Wijnaldum-Tjitsma revisited. Testing the potential value of field-surveying terp sites, in: A. Nieuwhof (ed.), *The excavations at Wijnaldum, Volume 2: Handmade and wheel-thrown pottery of the first millennium AD*, Groningen: Groningen Archaeological Studies 38, University of Groningen & Barkhuis Publishing, 193–240.

Kato, N., Y. Nakai & Y. Shindo 2009: Change in chemical composition of early Islamic glass excavated in Raya, Sinai Peninsula, Egypt: on-site analyses using a portable X-ray fluorescence spectrometer, *Journal of Archaeological Science*, 36, 1698–1707.

Keller, C., 2012: Karolingerzeitliche Keramikproduktion am rheinischen Vorgebirge, in: L. Grunwald, H. Pantermehl & R. Schreg (eds), *Hochmittel-alterliche Keramik am Rhein. Eine Quelle für Produktion und Alltag des 9. bis 12. Jahrhunderts*, Mainz: RGZM-Tagungen 13, 209–224.

Kind, T., A. Kronz & K.H. Wedepohl 2002: Karolinger-zeitliches Glas und verschiedene Handwerksindizien aus dem Kloster Fulda. Aufarbeitung der Altfunde Joseph Vonderaus von 1898–99, in: *Zeitschrift für Archäologie des Mittelalters*, 31, 2003, 2004: 61–93.

Koch, U., 1977: *Das Reihengräberfeld bei Schretzheim*, Berlin: Mann.

Koch, U., 1987: *Der runde Berg bei Urach VI, Die Glas- und Edelsteinfunde aus den Plangrabungen 1967–1983*, Heidelberger Akademie der Wissenschaften, Komm. Alamannische Altertumskunde 12, Sigmaringen.

Kouwatli, I., H.H. Curvers, B. Stuart, Y. Sablerolles, J. Henderson & P. Reynolds 2008: A pottery and glass production site in Beirut (BEY 015), *Bulletin d'Archéologie et d'Architecture Libanaise*, 10, 103–129.

Kronz, A., V. Hilberg, K. Simon & K.H. Wedepohl 2016: Glas aus Haithabu, *Zeitschrift für Archäologie des Mittelalters*, 43, 39–58.

Krüger, I. & K.H. Wedepohl 2003: Composition and shapes of glass of the early medieval period (8th to 10th century AD) in Central Europe, *Échanges et commerce du verre dans le monde antique*, 93–100.

Lahlil, S., I. Biron, M. Cotte, J. Susini & N. Menguy 2010: Synthesis of calcium antimonate nano-crystals by the 18th dynasty Egyptian glassmakers, *Applied Physics A*, 98(1), 1–8.

Langbroek, M., 2021a: Beads and beadmaking in the early medieval settlement at Oegstgeest, in: J. De Bruin, C. Bakels & F. Theuws (eds), *Oegstgeest. A riverine settlement in the early medieval world system*, Bonn, 2021, 278–293.

Langbroek, M.B., 2021b: Beads from Dorestad, in: A. Willemsen & H. Kik (eds), *Dorestad and its networks*, Proceedings of the third 'Dorestad Congress' held at the National Museum of Antiquities, Leiden, the Netherlands 12–15 June 2019: 55–99.

Lassaunière, G., I. Pactat, B. Gratuze & É. Louis 2016: L'artisanat du verre au haut Moyen Âge dans le nord de la France (Nord et Pas-de-Calais), *Bulletin de l'Association Française pour l'Archéologie du Verre*, 76–82.

Later, C., 2010: Von Trinkgläsern und Hängelampen, Gedanken zur Funktion frühmittel-alterlicher Sturzbecher, in: G. Suhr & K. Hösch (eds), *Bajuwarenhof Kirchheim – Projekt für lebendige Archäologie des frühen Mittelalters, Jahresschrift* 2009, München 2010, 65-76.

Louis, E., 2015: Les indices d'artisanat dans et autour du monastère de Hamage (Nord), *Bulletin du centre d'études médiévales d'Auxerre, BUCEMA* [on-line], Hors-série n° 8, mis en ligne le 28 janvier 2015: consulté le 16 décembre 2021. https://doi.org/10.4000/cem.13684.

Lund Feveile, L., 2006: Hulsglasskår fra markedspladsen i Ribe, ASR 9, Posthuset, in: C. Feveile (ed.), *Ribe Studier. DetÆldste Ribe. Udgravninger på nordsiden af Ribe Å 1984-2000, Bind 1.1* (Jysk Arkologisk Selskabs skrifter 51). Moesgård, 195-278.

Lundström, P., 1981: *De kommo vida ... Vikingars hamn vid Paviken på Gotland*, Stockholm (Sjöhistoriska museets rapportserie 15).

Magendans, J.R. & J.A. Waasdorp 1989: *Franken aan de Frankenslag. Een vroeg-middeleeuwse nederzetting in 's-Gravenhage*, 's-Gravenhage (VOM-reeks 1989-2).

Matin, M., 2019: Tin-based opacifiers in archaeological glass and ceramic glazes: a review and new perspectives, *Archaeological and Anthropological Sciences*, 11(4), 1155–1167.

Matin, M., M. Tite & O. Watson 2018: On the origins of tin-opacified ceramic glazes: New evidence from early Islamic Egypt, the Levant, Mesopotamia, Iran, and Central Asia. *Journal of Archaeological Science*, 97, 42–66.

Matthes, C., 1998: *Die Glasperlen des merowinger-zeitlichen Gräberfeldes Griesheim*, Magisterarbeit Berlin.

Meharg. A. A., K. J.Edwards, J. E. Scholfield, A. Raab, J. Feldmann, A. Moran, C. L. Bryant, B.Thornton & J.J. C. Dawson 2012: First comprehensive peat depositional records for tin, lead and copper associated with the antiquity of Europe's largest cassiterite deposits, *Journal of Archaeological* Science, 39, 717-727.

McCormick, M., 2001: *Origins of the European economy. Communications and commerce, AD 300–900*, New York: Cambridge University Press.

Meek, A., J. Henderson & J. Evans 2012: The isotopic analysis of English Forest glass from the Weald and Staffordshire, *Journal of Analytical Atomic Spectroscopy*, 27, 786–795.

Miedema, M., 1983: *Vijfentwintig eeuwen bewoning in het terpenland ten noordwesten van Groningen*, (PhD dissertation, Vrije Universiteit, Amsterdam).

Mirti, P., M. Pace, M.M. Negro Ponzi & M. Aceto 2008: ICP-MS analysis of glass fragments of Parthian and Sasanian epoch from Seleucia and Veh Ardašīr (central Iraq), *Archaeometry*, 50, 429–50.

Mirti, P., M. Pace, M. Malandreno & M. Negro Ponzi 2009: Sasanian glass from Veh Ardašīr: new evidences by ICP-MS analysis, *Journal of Archaeological Science*, 36, 1061–1069.

Nenna, M.-D., M. Vichy & M. Picon 1997: L'atelier de verrier de Lyon du Ier siècle après J.-C., et l'origine des verres "Romains", *Revue d'archéométrie*, 21 (1997), 81–87.

Nenna, M.-D., 2014: Egyptian glass abroad. HIMT glass and its markets, in: J. Bayley, C. Jackson, D. Keller & J. Price (eds) *Neighbours and successors of Rome. Traditions of glass production in use in Europe and the Middle East in the later first millennium AD*, Oxbow Books, Oxford, 178–193.

Nenna, M.-D., 2015: Primary glass workshops in Graeco-Roman Egypt: preliminary report on the excavations of the site of Beni Salama, Wadi Natrun (2003: 2005–9), in: Justine Bayley, I. Freestone & C. Jackson (eds), *Glass of the Roman world*, Oxbow Books, Oxford, 1–22.

Neri, E., B. Gratuze & N. Schibille 2018: The trade of glass beads in early medieval Illyricum: towards an Islamic monopoly, *Archaeological and Anthropological sciences* 11, 1107-1122. https://doi.org/10.1007/s12520-017-0583-5.

Nicolay, J.A.W., 2014: *The splendour of power. Early medieval kingship and the use of gold and silver in the southern North Sea area (5th to 7th century AD)*, Groningen: Groningen Archaeological Studies 28: Barkhuis & University of Groningen Library.

Nieuwhof, A., 2006: *De wierde Wierum (provincie Groningen). Een Archeologisch Steilkantonderzoek*, Groningen: Groningen Archaeological Studies 3.

Nieuwhof, A. (ed.) 2020: *The Excavations at Wijnaldum, Vol. 2: Handmade and wheel-thrown Pottery of the first Millennium AD*, Groningen: Groningen Archaeological Studies 34.

Nokkert, M., A.C. Aarts & H.L. Wynia 2009: *Vroegmiddeleeuwse bewoning langs de A2. Een nederzetting uit de zevende en achtste eeuw in Leidsche Rijn*, Utrecht (Basisrapportage archeologie 26 Gemeente Utrecht).

Norde, E.H.L.D., 2019: *Nederzettingsresten uit de vroege middeleeuwen in het plangebied Leeuwesteyn Noord in Leidsche Rijn, gemeente Utrecht*, Archeologisch onderzoek: een opgraving, Weesp: RAAP-Rapport 3855.

Nyst, C.L., 2003: *Karolingisch Glas van Dorestad. Een glasinventarisatie van vier opgravingen* , (unpublished BA thesis, University of Amsterdam).

Pactat, I., M. Guérit, L. Simon, B. Gratuze, S. Raux & C. Aunay 2017: Evolution of glass recipes during the Early Middle Ages in France: analytical evidence of multiple solutions adapted to local contexts, in: S. Sophie & A. Pury-Gysel (eds), Annales du 20e congrès de l'Association Internationale pour l'Histoire du Verre: Fribourg/Romont, 7–11 septembre 2015: Association Internationale pour l'Histoire du Verre, 334–340

Pactat, I., 2021: *L'activité verrière en France entre le viiie et le xie siècle. Résilience et mutations d'une production artisanale*, Thèse de doctorat en archéologie, sous la direction de Philippe Barral et de Danièle Foy, soutenue le 3 septembre 2020 à l'Université de Bourgogne Franche-Comté, Laboratoire Chrono-environnement/MSHE C.-N. Ledoux. *Bulletin du centre d'études médiévales d'Auxerre| BUCEMA*, (25.1). https://doi.org/10.4000/cem.18365

Paynter, S., 2008: Experiments in the reconstruction of Roman wood-fired glassworking furnaces: waste products and their formation processes, *Journal of Glass Studies*, 50, 271–290.

Peake, J.R. & I.C. Freestone 2012: Cross-craft interactions between metal and glass working: slag additions to early Anglo-Saxon red glass, in: W, Meulebroeck, K. Nys, D. Vanclooster & H. Thienpont (eds) *Integrated approaches to the study of historical glass*, IA1S 12, Proceedings of SPIE vol. 8422, 1-12, International Society for Optics and Photonics.

Peake, J.R. & I.C. Freestone 2014: Opaque yellow glass production in the early medieval period: new evidence, *Neighbours and successors of Rome: traditions of glass production and use in Europe and the Middle East in the later 1st millennium AD*. Oxford: Oxbow Books, 15–21.

Phelps, M., I.C. Freestone, Y. Gorin-Rosen & B. Gratuze 2016: Natron glass production and supply in the late antique and early medieval Near East: The effect of the Byzantine-Islamic transition, *Journal of archaeological science*, 75: 57–71.

Philippsen, B., C. Feveile, J. Olsen, J. & S. M. Sindbæk 2021: Single-year radiocarbon dating anchors Viking Age trade cycles in time, *Nature*. https://doi.org/10.1038/s41586-021-04240-5

Pion, C., 2014: *Les perles mérovingiennes. Typo-Chronologie, fabrications et fonctions*, Unpublished PhD Thesis, Université libre de Bruxelles, Brussels.

Pol, A., 1999: Munten, in: J. Plumier-Torfs, S. Plumier-Torfs, M. Regnard & W. Dijkman, *Mosa nostra. De Maasvallei van Verdun tot Maastricht in de Merovingische periode (5e-8e eeuw)*, Namur: Carnet du Patrimoine 28, 11.

Preiß, F., 2010: Tesserae and glass drops, in: A. Willemsen & H. Kik (eds), *Dorestad in an international framework. New research on centres of trade and coinage in Carolingian times*, Turnhout: Proceedings of the first 'Dorestad Congress' held at the Museum of National Antiquities Leiden, The Netherlands, June 24–27, 123–134.

Raux, S., B. Gratuze, J.-Y. Langlois & E. Coffineau 2015: Indices d'une production verrière du Xe siècle à La Milesse (Sarthe), *Bulletin de l'Association Française pour l'Archéologie du Verre*, Actes des 29e Rencontres, Paris (Nov. 2014), 66–70.

Redknap, M., 1988: Medieval pottery production at Mayen: recent advances, current problems, in: D.R.M. Gaimster, M. Redknap & H.-H. Wegner (eds), *Medieval and later pottery from the Rhineland and its markets*, Oxford: BAR Int. Series 440, 3–37.

Risom, T., 2013: *Perlemageren fra Ribe, Historien, Materialerne, Teknikkerne*, Ribe.

Rooksby, H.P., 1964: Yellow cubic lead-tin oxide opacifier in ancient glasses, *Physics and Chemistry of Glasses*, Section B of J. Soc. Glass Technol., 5, 20–25.

Rossi, R., 2009: Il vetro grezzo e le altre materie prime del reli tto romano di Mljet (Meleda), *Croazia Quaderni Friulani di Archeologia*, 19, 193-202.

Sablerolles, Y., 1992: Het glas van Gennep. De glasvondsten van een nederzetting uit de volksverhuizingstijk te Gennep (Zuid-Limburg). Doctorate thesis, University of Amsterdam.

Sablerolles, Y., 1993: A Dark-Age glass complex from a Frankish settlement at Gennep (Dutch Limburg), *Proceedings of the International Association for the history of glass*, Vienna 1991, Amsterdam: AIHV, 197-206.

Sablerolles, Y., 1999: Beads of glass, faience, amber, baked clay and metal, including the production waste from glass and amber bead making, in: J.C. Besteman, J.M. Bos, D.A. Gerrets, H.A. Heidinga & J. de Koning (eds), *The excavations at Wijnaldum. Reports on Frisia in Roman and Medieval Times* I, Rotterdam: Brookfield, 253–287.

Sablerolles, Y., 2019: Een smeltkroes voor glas uit de vroege middeleeuwen, in: E.H.L.D. Norde (ed.), *Nederzettingsresten uit de vroege middeleeuwen in het plangebied Leeuwesteyn Noord in Leidsche Rijn, deel 1, Gemeente Utrecht, Archeologisch onderzoek: een opgraving* (RAAP Rapport 3855), 136–138.

Sablerolles, Y., 2023: Glasproductie in het klooster van Susteren, Stoepker, H. (ed.), 2023: *Sporen van Susteren, archeologische vondsten uit een Karolingisch klooster en een adellijk vrouwenstift, de basispublicatie*, Venlo, 1249-1279. https://doi.org/10.17026/dans-xsf-nypw

Sablerolles, Y., J. Henderson & W. Dijkman 1997: Early medieval glass bead making in Maastricht (Jodenstraat 30), the Netherlands. An archaeological and scientific investigation, in: U. von Freeden & A. Wieczorek (eds), *Perlen. Archäologie, Techniken, Analysen*, Bonn: Akten Internat. Perlensymposium Mannheim 1994: Koll. Vor- und Frühgeschichte 1, 295–313.

Sablerolles, Y. & J. Henderson 2012: De glasvondsten, in: J. Dijkstra (ed.), *Het domein van de boer en de ambachtsman. Een opgraving op het terrein van de voormalige fruitveiling te Wijk bij Duurstede: een deel van Dorestad en de villa Wijk archeologisch onderzocht*, Amersfoort, (ADC monografie 12), 293–350.

Sablerolles, Y. & J. de Koning 2015: Kralen in het zand: de glasvondsten, in: J. de Koning, *Onder het stuifzand – Overstoven vroegmiddeleeuwse nederzettingen bij Bloemendaal. De opgravings-campagnes Groot Olmen 2005: 2006: en 2007: Inclusief een uitgebreide re-interpretatie van de opgraving Wijk aan Zee-Hoogovens uit de jaren zestig van de vorige eeuw*, Zaandijk, 307–320.

Sanke, M., K.H. Wedepohl & A. Kronz 2002: Karolinger-zeitliches Glas aus dem Kloster Lorsch, *Zeitschrift für Archäologie des Mittelalters*, 30, 37–75.

Schibille, N. & I.C. Freestone 2013: Composition, Production and Procurement of Glass at San Vincenzo al Volturno: An Early Medieval Monastic Complex in Southern Italy, PLoS One 8(10), e76479. https://doi.org/10.1371/journal.pone.0076479

Schibille, N., A. Sterrett-Krause & I.C. Freestone 2016. Glass groups, glass supply and recycling in Late Roman Carthage, *Archaeological and Anthropological Sciences*, 9, 1223–1241.

Schibille, N., A. Meek, B. Tobias, C. Entwistle, M. Avisseau-Broustet, H. Da Mota & B. Gratuze 2016: Comprehensive chemical characterisation of Byzantine glass weights. *PLoS One* 11(12), p.e0168289.

Schibille, N., B. Gratuze, E. Ollivier & É. Blondeau 2019: Chronology of early Islamic glass compositions from Egypt, *Journal of Archaeological Science*, 104, 10–18.

Schibille, N., J. de J. Ares, M.T.C. García & C. Guerrot 2020: Ex novo development of lead glassmaking in early Umayyad Spain, Proceedings of the National Academy of Sciences 117 (28) 16243-16249; https://doi.org/10.1073/pnas.2003440117

Schibille,N., V. Amorós Ruiz, J. De Juan Ares & S. Gutiérrez Lloret 2022: Rare alkali elements as markers of local glass working in medieval Tolmo de Minateda (Spain), *ChemPlusChem* 87, e202200147.

Shortland, A.J., 2004: Evaporites of the Wadi Natrun: Seasonal and annual variation and its implication for ancient exploitation, *Archaeometry*, 46, 4: 497–517.

Sier, M.M., J. van Doesburg & W.J.H. Verwers (eds) 2004: *Wijk bij Duurstede-Frankenweg/Zandweg*, Amersfoort (ADC-rapport 282).

Silvestri, A., G. Molin & G. Salviulo 2008: The colourless glass of Iulia Felix, *Journal of archaeological science*, 35(2), 331–341.

Silvestri, A., S. Tonietto, G. Molin & P. Guerriero 2012: The palaeo-Christian glass mosaic of St. Prosdocimus (Padova, Italy): archaeometric characterisation of tesserae with antimony- or phosphorus-based opacifiers, *Journal of archaeological science*, 39(7), 2177–2190.

Simpson, S.J., 2014: Sasanian glass: an overview, in: D. Keller, J. Price, & C. Jackson (eds), *Neighbours and Successors of Rome. Traditions of Glass Production and Use in Europe and the Middle East in the Later 1st Millennium AD*, Oxford: Oxbow Books, 200–231.

Siu, I., J. Henderson, D. Qin, Y. Ding, J. Cui & and H. Ma 2020: New light on plant ash glass found in Africa: Evidence for Indian Ocean Silk Road trade using major, minor, trace element and lead isotope analysis of glass from the 15th—16th century AD from Malindi and Mambrui, Kenya, *PLoS One*, 15, p. e0237612.

Smith, T., J. Henderson & E.W. Faber 2016: Early Byzantine glass supply and consumption: the case of Dichin, Bulgaria, in: Guxi Gan, Julian Henderson & Qinghui Li (eds), *Recent research in the scientific investigations of ancient glass*, World Scientific, 207–232.

Sode, T., 2004: Glass bead making technology, in: M. Bencard, A.K. Rasmussen & H.B. Madsen (eds), *Ribe excavations 1970–76* (Vol. 5), Moesgard: Jutland Archaeological Society, 83–102.

Standish, C.D., S.W. Merkel, Y.-T. Hsieh, & J. Kershaw 2021: Simultaneous lead isotope ratio and gold-lead-bismuth concentration analysis of silver by laser ablation MC-ICP-MS, *Journal of Archaeological Science* 125, 105299.

Steppuhn, P., 1998: *Die Glasfunde von Haithabu*, Berichte über die Ausgrabungen in Haithabu 32, Neumünster.

Stoepker, H., 2021: *Het klooster van Susteren (714–1802). Archeologisch onderzoek van een Karolingische abdij en een adellijk vrouwenstift*, Amersfoort (Nederlandse Archeologische Rapporten 73).

Szöke, B.M., K.H. Wedepohl & A. Kronz 2004: Silver-stained windows at Carolingian Zalavar, Mosaburg (southwestern Hungary), *Journal of Glass Studies* 46, 85–104

Tal, O., E.E. Jackson-Tal & I.C. Freestone 2004: New evidence for glass production at Lat Byzantine Apollonia-arsuf, Israel, *Journal of Glass Studies*, 51, 51–65.

Thedéen, S., 2009: Who's that girl? The cultural construction of girlhood and the transition to womanhood in Viking Age Gotland, *Childhood in the Past* 1(1), 78–93.

Van Dockum, S.G., 1997: Parkeerplaats AH, in: *Archeologische Kroniek Provincie Utrecht 1992–1993*, Utrecht, 120–121.

Van Doesburg, J., 2004: Glas, in: M.M. Sier, J. van Doesburg & W.J.H. Verwers (eds), *Wijk bij Duurstede-Frankenweg/Zandweg*, Amersfoort (ADC-rapport 282), 42.

Van Es, W.A. & W.J.H. Verwers 1980: *Excavations at Dorestad 1. The harbour: Hoogstraat 1*, Amersfoort: Nederlandse Oudheden 9.

Van Lith, S.M.E. & Y. Sablerolles 1995: Verres du IVe et du Ve siècle des sites d'habitat aux Pays-Bas, in: F. Foy (ed.) *Le verre de l'antiquité tardive et du haut moyen âge*, Association Française pour l'Archéologie du Verre, huitième rencontre, Guiry-en-Vexin, 18-19 Novembre 1993, 41-50.

Van Os, B.J.H., R.M. Vogelzang, J.W. de Kort, D.J. Huisman, M. Kars, D.J.M. Ngan-Tillard, W. Verwaal & E. Meijvogel 2014: Kralen van glas en barnsteen, in: R.C.G.M. Lauwerier & J.W. de Kort (eds), *Merovingers in een villa 2, Romeinse villa en Merovingisch grafveld Borgharen – Pasestraat Onderzoek*, Amersfoort (Rapportage Archeologische Monumentenzorg 222).

Van Wersch, L.F. 2013: Merovingian ceramic and glass in the early towns of the middle Meuse valley, *Medieval and modern matters* 4, 133-151.

Van Wersch, L., F. Mathis & P. Hoffsummer 2009: Étude des verres du Haut Moyen Âge découverts dans l'église des saints Hermès et Alexandre à Theux, in: *Vitrail, Verre et Archéologie entre le Ve et le XIIe siècle, Actes de la table ronde réunie au Centre d'Études Médiévales d'Auxerre, 15–16 juin 2006*, Paris, 161–171.

Van Wersch, L., I. Biron, B. Neuray, F. Mathis, G. Chêne, D. Strivay & C. Sapin 2014: Les vitraux alto-médiévaux de Stavelot (Belgique), *ArchéoSciences* 38, 219–234.

Van Wersch, L., C. Loisel, F. Mathis, D. Strivay & S. Bully 2015: Analyses of Early Medieval Stained Window Glass from the Monastery of Baume-les-Messieurs (Jura, France), *Archaeometry*, 58, 930–946.

Van Wersch, L., B. Gratuze, F. Mathis, M. Bonnin, D. Strivay, H. Da Mota Rocha & C. Sapin 2018: Glass tiles from Saint-Sauveur (Burgundy, France), *Journal of Glass Studies*, 60, 163-181.

Van Winkelhoff, A.M., 2021: Light in the Dark Ages: a conceptual approach to the role of glass vessels in the Merovingian burial rite, (RMA-thesis Leiden University, Leiden).

Verhulst, A., 2002: *The Carolingian Economy*, Cambridge Medieval Texbooks, Cambridge: Cambridge University Press.

Vollgraff, C.W. & G. van Hoorn 1934: *Opgravingen op het Domplein te Utrecht*, Wetenschappelijke Verslagen II, De opgravingen in juni en juli 1933: Haarlem.

Vrielynck, O., F. Mathis & C. Pion 2018: *Vers une typo-chronologie des perles mérovingiennes en Gaule du Nord*, Namur.

Wedepohl, K.H., 2003: *Flach- und Gefäßglas der Karolingerzeit*, Nachrichten der Akademie der Wissenschaften Göttingen, II. Mathematische–Physikalische, Klasse, 3, 115–156.

Wedepohl, K.H., 2008: Mittelalterliches Holzasche-Glas, in: H. Flachenecker, G. Himmelsbach & P. Steppuhn (eds), *Glashüttenlandschaft Europa*, Regensburg: Schnell and Steiner.

Wedepohl, K. H. & A. Baumann 1997: Isotope composition of Medieval lead glasses reflecting early silver production in Central Europe, *Mineralium Deposita* 32, 292–295.

Wedepohl, K.H. & K. Simon 2010: The chemical composition of medieval wood ash glass from Central Europe, *Geochemistry*, 70(1), 89–97.

Wedepohl, K.H., W. Winkelmann & G. Hartmann 1997: Glasfunde aus der karolingischen Pfalz in Paderborn und die frühe Holzasche-Glasherstellung, *Ausgrabungen und Funde in Westfalen Lippe*, 9A, 41–53.

Willmott, H. & K. Welham 2013: Late seventh-century glassmaking at Glastonbury Abbey, *Journal of Glass Studies* 55, 71–83.

Willmott, H. & K. Welham 2015: Saxon Glass Furnaces, in: R. Gilchrist & C. Greene (eds) *Glastonbury Abbey: archaeological investigations 1904–79*, Society of Antiquaries of London, London, 218–238.

Wynia, H., 2013: Graven op het Domplein, in: *DompleinMagazine, Special I: Het Domplein in Utrecht*, Utrecht, 9–15.

Yener, K.A., F. Kulakoğlu, E. Yazgan, R. Kontani, Y.S. Hayakawa, J.W. Lehner, G. Dardeniz, G. Öztürk, M. Johnson, R. Kaptan & A. Hacar 2015: New tin mines and production sites near Kültepe in Turkey: a third-millennium BC highland production model, *Antiquity*, 89, 596-612.

Appendices

Appendix I sample list

The list of the samples from the different sites used in this study: Maastricht (Jodenstraat and Mabro sites), Gennep, Wijnaldum, Utrecht, Wijk bij Duurstede (Dorestad), Susteren and Deventer.

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Maastricht-Jodenstraat	1	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	2	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	3	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	4	01-01-2007	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	5	1-1-7	1/7	pit	580/90	610/20	production waste	thread
Maastricht-Jodenstraat	6	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Mabro	7	3-4-0	0	pit	-	-	production waste	crucible
Maastricht-Mabro	8	3-OA-55	3/55	pit	-	-	production waste	crucible
Maastricht-Mabro	9	1-3-51	1/51	pit	-	-	production waste	crucible?
Maastricht-Mabro	10	3-OA-1	3/1	pit	-	-	production waste	crucible
Maastricht-Mabro	11	1-5-OA	1/OA	pit	-	-	production waste	crucible
Maastricht-Mabro	12	3-AA'-400	3/400	pit	-	-	production waste	crucible
Maastricht-Mabro	13	2-2-18	2/18	pit	-	-	production waste	crucible
Maastricht-Mabro	14	3-5-24	3/24	pit	-	-	production waste	crucible
Maastricht-Mabro	15	3-5-24	3/24	pit	-	-	production waste	crucible
Maastricht-Mabro	16	3-4-12	3/12	pit	-	-	production waste	crucible
Maastricht-Jodenstraat	17	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	18	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	19	1-1-7	1/7	pit	580/90	610/20	production waste	crucible

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
section	-	rod, red with weathered surface	-	opaque	-	x	2	Sablerolles *et al.* 19997
section	-	rod, red with weathered surface	-	opaque	-	x	2	Sablerolles *et al.* 19997
section	-	white twisted rod	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	white rod	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	white rod (thin, c 2-3 mm)	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	yellow rod > 5 mm	-	opaque	-	-	2	Sablerolles *et al.* 19997
rim	-	crucible rim fragment with white material (frit?) on both sides	-	opaque	-	-	2	Sablerolles *et al.* 19997
body	-	crucible base fragment with colourless glass on both sides, white on the inside	-	opaque/ translucent	-	-	2	Sablerolles *et al.* 19997
?	-	small crucible fragment with green and weathered opaque yellow glass	-	translucent/ opaque	-	x	2	Sablerolles *et al.* 19997
rim	-	crucible rim with colourless glass on inside	-	transparent	-	-	2	Sablerolles *et al.* 19997
rim	-	crucible rim fragment with thick white material (frit?) on both sides; colourless glass on the inside	-	opaque/ transparent	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base fragment with opaque yellow glass on inside. colourless vitrification on the outside.	-	opaque/ transparent	-	-	2	Sablerolles *et al.* 19997
ceramic	-	small fragment of red ceramic with (natural?) green glass on both sides	-	translucent	-	-	2	Sablerolles *et al.* 19997
base	-	red ceramic pot base with yellow (outside) and yellow-colourless (inside) glass	-	opaque/ transparent	-	-	2	Sablerolles *et al.* 19997
ceramic	-	small ceramic fragment with deep translucent glass on inside	-	transparent	-	-	2	Sablerolles *et al.* 19997
base	-	thick red ceramic base with deep translucent green glass on both sides, partially weathered glass on both sides	-	transparent	-	x	2	Sablerolles *et al.* 19997
base	-	crucible base of reddish-grey ceramic with opaque yellow glass on inside	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of grey ceramic, with weathered opaque yellow glass on inside.	-	opaque	-	x	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, weathered opaque yellow glass on inside	-	opaque	-	x	2	Sablerolles *et al.* 19997

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Maastricht-Jodenstraat	20	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	21	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	22	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	23	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	24	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	25	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	26	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	27	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	28	1-1-7	1/7	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	29	1-2-3	1/3	pit	580/90	610/20	production waste	crucible
Maastricht-Jodenstraat	30	1-1-7	1/7	pit	580/90	610/20	production waste	brick/tegula?
Maastricht-Jodenstraat	37	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	38	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	39	1-1-7	1/7	pit	580/90	610/20	production waste	ingot?
Maastricht-Jodenstraat	40	1-1-7	1/7	pit	580/90	610/20	production waste	ingot?
Maastricht-Jodenstraat	41	1-1-7	1/7	pit	580/90	610/20	production waste	punty?
Maastricht-Jodenstraat	42	1-1-7	1/7	pit	580/90	610/20	production waste	punty?
Maastricht-Jodenstraat	43	1-1-7	1/7	pit	580/90	610/20	production waste	punty?
Maastricht-Jodenstraat	44	1-2-3	1/3	pit	580/90	610/20	window	flat quite thick window glass; one side worked with grozing (sp.) iron?
Maastricht-Jodenstraat	45	1-2-3	1/3	pit	580/90	610/20	window	thin window glass; two sides been worked with grozing (sp.) iron?

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
base	-	crucible base of red ceramic, layer of opaque yellow glass on inside	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of thin grey ceramic, colourless glass	-	translucent	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base with opaque yellow glass and white material	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base with opaque yellow glass and white material	-	opaque/ translucent	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, opaque yellow and brownish red vitrification	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, opaque yellow and redish-brown vitrification	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, opaque yellow glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, opaque yellow glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, opaque yellow glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	crucible base of red ceramic, deep translucent green glass, esp. thick on bottom	-	translucent	-	-	2	Sablerolles *et al.* 19997
-	-	possible furnace brick fragment with weathered opaque yellow glass	-	opaque	-	x	2	Sablerolles *et al.* 19997
complete	-	blue glass drop, c. 1 cm	-	translucent	-	-	2	Sablerolles *et al.* 19997
complete	-	blue glass drop, c. 1 cm	-	translucent	-	-	2	Sablerolles *et al.* 19997
crushed	-	small (crushed?) blue glass fragments	-	translucent	-	-	2	Sablerolles *et al.* 19997
crushed	-	small (crushed?) blue glass fragments	-	translucent	-	-	2	Sablerolles *et al.* 19997
undiagnostic	-	fragment of opaque red glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
undiagnostic	-	fragment of opaque red glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
undiagnostic	-	fragment of blue-green glass	-	translucent	-	x	2	Sablerolles *et al.* 19997
-	-	flat quite thick translucent yellowish window glass; one side worked with grozing (sp.) iron?	-	translucent	-	-	2	Sablerolles *et al.* 19997
-	-	thin amber window glass; two sides been worked with grozing iron	-	translucent	-	-	2	Sablerolles *et al.* 19997

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Maastricht-Jodenstraat	46	1-2-3	1/3	pit	580/90	610/20	window	moderately thin window glass. One side rounded.
Maastricht-Jodenstraat	47	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	48	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	49	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	50	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	51	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	52	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	53	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	54	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	55	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	56	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	57	1-1-3	1/3	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	58	?	-	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	59	?	-	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	60	1-2-5	1/5	pit	580/90	610/20	vessel	cone
Maastricht-Jodenstraat	61	1-2-5	1/5	pit	580/90	610/20	bead	bead
Maastricht-Jodenstraat	62	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	63	1-1-7	1/7	pit	580/90	610/20	production waste	drop
Maastricht-Jodenstraat	64	1-1-7	1/7	pit	580/90	610/20	production waste	?
Maastricht-Jodenstraat	65	1-1-7	1/7	pit	580/90	610/20	production waste	?
Maastricht-Jodenstraat	66	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	67	1-1-7	1/7	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	68	1-1-7	1/7	pit	580/90	610/20	vessel	ribbed bowl
Maastricht-Jodenstraat	69	1-1-7	1/7	pit	580/90	610/20	production waste	punty

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered

Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
-	-	moderately thin pale green window glass. one side rounded.	-	translucent	-	-	2	Sablerolles *et al.* 19997
section	-	thin opaque olive green rod	-	opaque	-	-	2	Sablerolles *et al.* 19997
-	-	opaque green drop	-	opaque	-	-	2	Sablerolles *et al.* 19997
-	-	irregular green drop with soil fused to it	-	translucent	-	-	2	Sablerolles *et al.* 19997
-	-	drop of weathered opaque yellow glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
-	-	irregular drop of reddish glass	-	opaque	-	-	2	Sablerolles *et al.* 19997
-	-	irregular drop of deep translucent ('black') glass	-	translucent	-	x	2	Sablerolles *et al.* 19997
-	-	stretched pale opaque blue piece of rod?	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	thin opaque red rod with weathered exterior	-	opaque	-	x	2	Sablerolles *et al.* 19997
-	-	irregular red drop, weathered surface	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	double rod; yellow with slightly greenish tint	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	blue-green rod	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	twisted opaque white rod	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	white rod	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	-	base of translucent green cone	-	translucent	-	-	2	Sablerolles *et al.* 19997
half	-	fragmented tapering cobalt blue bead	-	opaque	-	-	2	Sablerolles *et al.* 19997
drop	-	drop; naturally coloured yellowish	-	translucent	-	-	2	Sablerolles *et al.* 19997
drop	-	irregular drop; naturally coloured yellowish	-	translucent	-	-	2	Sablerolles *et al.* 19997
undiagnostic	-	thin opaque yellow fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
undiagnostic	-	thin opaque yellow fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	rod, red with weathered surface	-	opaque	-	x	2	Sablerolles *et al.* 19997
section	-	rod, red with weathered surface	-	opaque	-	x	2	Sablerolles *et al.* 19997
ribbed bowl	-	quite thick blue green glass fragment with a rib (roman?)	-	translucent	-	-	2	Sablerolles *et al.* 19997
-	-	"punty glass" yellow thin-walled fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Maastricht-Jodenstraat	70	1-1-7	1/7	pit	580/90	610/20	production waste	punty
Maastricht-Jodenstraat	71	1-1-7	1/7	pit	580/90	610/20	production waste	punty
Maastricht-Jodenstraat	72	1-1-7	01-jul	pit	580/90	610/20	production waste	punty
Maastricht-Jodenstraat	73	?	?	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	74	?	?	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	75	?	?	pit	580/90	610/20	production waste	rod
Maastricht-Jodenstraat	76	?	?	pit	580/90	610/20	production waste	rod
Gennep	GE 41	4481	35/2	sunken hut	400	550	vessel	cone
Gennep	GE 42	4060	28/8	sunken hut	400	550	vessel	cone
Gennep	GE 43	1749	13/34	sunken hut	400	550	vessel	cone
Gennep	GE 44	2115	20/37	sunken hut	400	550	vessel	cone
Gennep	GE 45	3079	19/26	sunken hut	400	550	vessel	cone
Gennep	GE 46	2527	6/10	sunken hut	400	550	vessel	cone
Gennep	GE 47	2557	7/120	sunken hut	400	550	vessel	cone
Gennep	GE 48	1313	8/54	sunken hut	400	550	vessel	cone
Gennep	GE 49	2278	6/1	sunken hut	400	550	vessel	cone
Gennep	GE 50	1399	8/35	sunken hut	400	550	vessel	cone
Gennep	GE 51a	2795	10/38	well	400	550	vessel	cone
Gennep	GE 51b	1397	8/35	sunken hut	400	550	vessel	cone
Gennep	GE 52	-	-	-	400	550	vessel	cone
Gennep	GE 53	2598	10/1	sunken hut	400	550	vessel	bowl
Gennep	GE 54	4254	27/13	sunken hut	400	550	vessel	bowl

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
-	-	"punty glass" yellow thin-walled fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
-	-	"punty glass" yellow thin-walled fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
-	-	"punty glass" yellow thin-walled fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	turquoise green rod fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	turquoise green rod fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	green rod fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
section	-	green rod fragment	-	opaque	-	-	2	Sablerolles *et al.* 19997
base	Koch 1987 III?	-	yellow-green	translucent	-	-	1	Sablerolles 1992, cat. 121.1
base	Koch 1987 III I	-	olive brown	-	-	-	1	Sablerolles 1992, cat. 85.1
base	Koch 1987 III?	-	olive green	-	-	-	1	Sablerolles 1992, cat. 134.2?
rim	Koch 1987 III H	-	olive green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 81.6
rim	Koch 1987 III?	-	light blue-green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 127.1
rim	Koch 1987 III I	-	yellow-green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 86.3
rim	Koch 1987 III?	-	pale yellow/ colourless	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 124.1
rim	Koch 1987 III?	-	pale green/ colourless	-	white spiral	-	1	Sablerolles 1992, cat. 123.1
rim	Koch 1987 III I?	-	pale green/ colourless	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 155.2
rim	Isings 1957 106b2?	-	yellow-green	-	brown spiral	-	Roman	Sablerolles1992, cat. 2.3
rim	Isings 1957 106c2?	-	yellow-green	-	brown spiral	-	Roman	Sablerolles 1992, cat. 5.1
body	Isings 1957 106c2?	-	yellow-green	-	brown arcades	-	Roman	Sablerolles 1992, cat. 5.2
rim	Koch 1987 III?	-	light yellow-green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. -
rim	Koch 1987 IV K	-	light yellow-green/ colourless	-	-	-	1	Sablerolles 1992, cat. 141.1
rim	Koch 1987 IV M	-	light green-yellow	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 17

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Gennep	GE 55	-	-	-	400	550	vessel	bowl
Gennep	GE 56	1915	16/38	sunken hut	400	550	vessel	bowl
Gennep	GE 57	-	-	-	400	550	vessel	bowl
Gennep	GE 58	-	-	-	400	550	vessel	bowl
Gennep	GE 59	-	-	-	400	550	vessel	bowl
Gennep	GE 60	4549	35/2	sunken hut	400	550	vessel	bowl
Gennep	GE 61	4549	35/2	sunken hut	400	550	vessel	bowl
Gennep	GE 62	4464	35/2	sunken hut	400	550	vessel	bowl
Gennep	GE 63	4563	35/2	sunken hut	400	550	vessel	bowl
Gennep	GE 64	4549	35/2	sunken hut	400	550	vessel	bowl
Gennep	GE 65	4901	41/3	post hole sunken hut	400	550	vessel	bowl
Gennep	GE 66	4257	32/20	pit	400	550	vessel	bowl
Gennep	GE 67	1316	8/54	sunken hut	400	550	vessel	bowl
Gennep	GE 68	1512	8/8	sunken hut	400	550	vessel	bowl
Gennep	GE 69	1500	8/8	sunken hut	400	550	vessel	bottle
Wijnaldum	WIJ 1	9782	2351	occupation surface	450	500	vessel	cone (Kempston)
Wijnaldum	WIJ 2	6794	1346	waste deposit?	450	500	vessel	bowl
Wijnaldum	WIJ 3	10802	2565	sunken hut/ waste deposit	600	700	vessel	bowl
Wijnaldum	WIJ 4	6242	801	ditch	450	500	bead	small glob
Wijnaldum	WIJ 5	1356	625	area with metal waste/ waste deposit	575	625	bead	small glob
Wijnaldum	WIJ 6	1428	608	well 9	575	625	bead	small glob

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
rim	Koch 1987 IV M	-	pale green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. -
rim	Koch 1987 IV M	-	pale blue-green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 172.1
rim	Koch 1987 IV M	-	pale green/ colourless	-	self-coloured spiral	-	1	Sablerolles 1992, cat. 173.2
body	Koch 1987 IV M	-	pale green	-	self-coloured spiral	-	1	Sablerolles1992, cat. -
base	Koch 1987 IV M	-	light yellow-green	-	self-coloured spiral	-	1	Sablerolles 1992, cat. -
rim	Koch 1987 IV B?	-	light yellow/ colourless	-	-	-	1	Sablerolles 1992, cat. 136.2
base	Koch 1987 IV B?	-	light yellow/ colourless	-	-	-	1	Sablerolles 1992, cat. 136.3
body	Koch 1987 IV K	-	light yellow-green/ colourless	-	white festoons	-	1	Sablerolles 1992, cat. 147.1
rim	Koch 1987 IV L	-	light green-blue/ colourless	-	white feather	-	1	Sablerolles 1992, cat. 151.5
rim	Koch 1987 IV L	-	light green-blue	-	white feather	-	1	Sablerolles 1992, cat. 151.5
rim	Koch 1987 IV L	-	light green-yellow/ colourless	-	white feather	-	1	Sablerolles 1992, cat. 154.1
body	Koch 1987 IV L	-	light blue-green	-	white feather	-	1	Sablerolles 1992, cat. 150.1
base	Koch 1987 IV ?	-	light blue-green	-	-	-	1	Sablerolles 1992, cat. 162
body	Koch 1987 IV ?	-	light blue-green	-	-	-	1	Sablerolles 1992, cat. 161
body	Isings 1957 101	-	yellow-green	-	red streaks	-	Roman	Sablerolles 1992, cat. 1.3
body	Koch 1987 III N	-	pale bluish green	transparent	self-coloured loops	x	1	Sablerolles 1999 VESSEL cat. 7
rim	Koch 1987 IV L	-	pale bluish green	transparent	white feather	x	1	Sablerolles 1999 VESSEL fig. 1.9
rim	Koch 1987 IV	-	light bluish green	transparent	white spiral	x	1	Sablerolles 1999 VESSEL cat. 10
complete	Pion 2014 B1.1-2b	-	yellow	opaque	-	-	1	Sablerolles 1999, BEAD fig. 5.13
-	Pion 2014 B1.1-2a	-	yellow	opaque	-	-	2	Sablerolles 1999 BEAD cat. 14
-	Pion 2014 B1.1-2b	-	yellow	opaque	-	-	2	Sablerolles 1999 BEAD cat. 15

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Wijnaldum	WIJ 7	1462	1167	sod layer	600	700	bead	small glob
Wijnaldum	WIJ 8	3901	574	ditch	575	625	bead	small glob
Wijnaldum	WIJ 9	3901	574	ditch	575	625	bead	small glob
Wijnaldum	WIJ 10	3695	2605	truncated layer/waste deposit	800	850	vessel	funnel
Wijnaldum	WIJ 11	7359	1636	truncated layer/waste deposit	800	900	vessel	funnel
Wijnaldum	WIJ 12	7507	3296	truncated layer/ occupation surface	775	850	vessel	funnel
Wijnaldum	WIJ 13	7877	3358	truncated layer/ ooccupation surface	800	850	vessel	funnel
Wijnaldum	WIJ 14	6704	1233	ditch	550	600	bead	small glob
Wijnaldum	WIJ 15	10906	340	occupation surface	770	900	vessel	funnel
Wijnaldum	WIJ 16	1526	1114	sod layer	700	750	vessel	jar?
Wijnaldum	WIJ 17	5812	2098	occupation surface/waste deposit	450	550	bead	small glob
Wijnaldum	WIJ 18	6712	1330	occupation surface	450	550	bead	small annular
Wijnaldum	WIJ 19	5534	1233	ditch	550	600	bead	small glob
Wijnaldum	WIJ 20	7448	1233	ditch	550	600	bead	small glob
Wijnaldum	WIJ 21	2655	625	met/wd	575	625	bead	small glob
Wijnaldum	WIJ 22	5632	975	cultivation layer	550	560	bead	small glob
Wijnaldum	WIJ 23	6704	6704	ditch	550	600	bead	small glob
Wijnaldum	WIJ 24	1461	548	occupation surface/waste desposit	550	600	bead	short cylindrical
Wijnaldum	WIJ 25	5666	1232	ditch	550	650	bead	short cylindrical
Wijnaldum	WIJ 26	7448	1233	ditch	550	600	bead	short cylindrical
Wijnaldum	WIJ 27	2454	558	cultivation layer	500	550	bead	short cylindrical

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
-	Pion 2014 B1.1-2a	-	yellow	opaque	-	-	2 or 3	Sablerolles 1999 BEAD cat. 16
-	Pion 2014 B1.1-2a	-	yellow	opaque	-	-	2	Sablerolles 1999 BEAD cat. 18
-	Pion 2014 B1.1-2a	-	yellow	opaque	-	-	2	Sablerolles 1999 BEAD cat. 19
rim	Lund Feveil 2006, rim type e	-	light (blue-) green	translucent	-	x	4	Sablerolles 1999 VESSEL fig. 1.20
rim	Lund Feveil 2006, rim type e	-	almost colourless	transparent	-	x	4	Sablerolles 1999 VESSEL fig. 1.21
rim	Lund Feveil 2006, rim type d	-	yellowish green	translucent	-	x	4	Sablerolles 1999 VESSEL fig. 1.22
rim	Lund Feveil 2006, rim type e	-	almost colourless	transparent	-	x	4	Sablerolles1999 BEAD fig. 1.23
-	Pion 2014 B1.1-02b	-	yellow	opaque	-	-	2	Sablerolles 1999 BEAD cat. 25
rim	Lund Feveil 2006, rim type g	-	dark blue	translucent	incalmo rim	x	4	Sablerolles 1999 VESSEL fig. 1.26
rim	-	-	blue-green	translucent	yellow spiral, white arcade	-	3/4	Sablerolles 1999 VESSEL fig. 1.30
-	Pion 2014 B1.1-3b	-	red	opaque	-	-	2	Sablerolles 1999 BEAD cat. 46
complete	Pion 2014 B1.1-3b	-	red	opaque	-	-	2	Sablerolles 1999 BEAD fig. 5.47
-	Pion 2014 B1.1-3b	-	red	opaque	-	-	2	Sablerolles 1999 BEAD cat. 49
-	Pion 2014 B1.1-3b	-	red	opaque	-	-	2	Sablerolles1999 BEAD cat. 53
-	Pion 2014 B.1.1-4a	-	white	opaque	-	-	2	Sablerolles 1999 BEAD cat. 56
-	Pion 2014 B.1.1-4a	-	white	opaque	-	-	2	Sablerolles 1999 BEAD cat. 57
complete	Pion 2014 B1.1-4a	-	white	opaque	-	-	2	Sablerolles 1999, fig. 5.58
complete	Pion 2014 B1.4-1a	-	yellow	opaque	-	-	2	Sablerolles 1999, fig. 5.66
-	Pion 2014 B1.4-3a	-	white	opaque	-	-	2	Sablerolles 1999 BEAD cat. 73
-	Pion 2014 B1.4-3a	-	white	opaque	-	-	2	Sablerolles 1999 BEAD cat. 78
-	Pion 2014 B1.4-2a	-	red	opaque	-	-	2	Sablerolles 1999 BEAD cat. 80

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Wijnaldum	WIJ 28	10824	1384	truncated layer/waste deposit	650	750	bead	short cylindrical
Wijnaldum	WIJ 29	11090	2546	ditch	650	750	bead	short cylindrical
Wijnaldum	WIJ 30	6884	575	well 8	770	850	bead	short cylindrical
Wijnaldum	WIJ 31	7448	1233	ditch	550	600	bead	short cylindrical
Wijnaldum	WIJ 32	1024	1079	sod layer	640	750	bead	biglobular
Wijnaldum	WIJ 33	6704(2)	1233	ditch	550	600	bead	biglobular
Wijnaldum	WIJ 34	6562(1)	2064	sod layer	500	550	bead	irregular spiral
Wijnaldum	WIJ 35	3316(2)	3532	pit?	775	850	bead	segmented, 'gold' foil
Wijnaldum	WIJ 36	6562(1)	2064	sod layer	500	550	bead	segmented, gold foil
Wijnaldum	WIJ 37	3326(1)	3542	ditch/ occupation surface?	875	900	bead	segmented, silver foil
Wijnaldum	WIJ 38	9737(1)	2341	occupation surface/sod layer	450	500	bead	segmented, silver foil
Wijnaldum	WIJ 39	10608(1)	100	well 6	750	850	bead	segmented, layered
Wijnaldum	WIJ 40	10786	514	ditch	750	770	production waste	tessera
Wijnaldum	WIJ 41	3829	696	occupation suface	425	500	production waste	rod
Wijnaldum	WIJ 42	4601	2817	truncated layer/ occupation surface	750	800	production waste	punty glass
Wijnaldum	WIJ 43	2943	625	area with metal waste	575	625	production waste	furnace?
Utrecht-Domplein	31	1933-77-36	?	?	-	-	production waste	crucible
Utrecht-Domplein	32	1933-77-53	?	?	-	-	production waste	crucible
Utrecht-Domplein	33	1933-zn3	?	?	-	-	production waste	crucible
Utrecht-Domplein	34	1933-234	?	?	-	-	production waste	crucible

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
-	Pion 2014 B1.4-2a	-	red	opaque	-	-	3	Sablerolles 1999 BEAD cat. 81
-	Pion 2014 B1.4-2a	-	red	opaque	-	-	3	Sablerolles 1999 BEAD cat. 82
-	Callmer 1977 A135?	-	red	opaque	-	-	4	Sablerolles 1999 BEAD cat. 83
-	Pion 2014 B1.4-2a	-	red	opaque	-	-	2	Sablerolles 1999 BEAD cat. 84
-	Pion 2014 B1.2-1b	-	yellow	opaque	-	-	3	Sablerolles 1999 BEAD cat. 97
-	Pion 2014B1.2-1b	-	yellow	opaque	-	-	2	Sablerolles 1999 BEAD cat. 99
-	Pion 2014 B1.8-01	-	black/dark blue	opaque	-	-	1	Sablerolles 1999 BEAD cat. 102
complete?	Callmer 1977 E140?	-	yellowish?	transparent	-	-	4	Sablerolles 1999 BEAD, fig. 5.115
-	Pion 2014 A4.1-1	-	colourless	transparent	-	-	1	Sablerolles 1999 BEAD cat. 116
complete	Callmer 1977 E140?	-	colourless	transparent	-	-	4	Sablerolles 1999 BEAD, fig. 5.118
-	Pion 2014 A4.2-1	-	colourless	transparent	-	-	1	Sablerolles1999 BEAD cat. 119
complete	Pion 2014 A3.1-7	-	red on colourless	opaque	-	-	4	Sablerolles1999 BEAD, fig. 5.122
-	-	-	yellow	opaque	-	-	Roman	Sablerolles 1999, fig. 4, cat. 216
-	-	-	greenish white	opaque	-	-	1	Sablerolles 1999, fig. 4, cat. 217
-	-	-	turquoise	opaque	-	-	4	Sablerolles 1999, fig. 4, cat. 218
-	-	-	yellow	opaque	-	x	2	Sablerolles 1999, fig. 3, cat. 219
body?	-	crucible fragment (one of two), thin-walled grey ceramic with a thin layer of green glass	-	translucent	-	-	4	-
body?	-	crucible fragment, thin-walled beige ceramic with a thin (cracked) layer of green glass.	-	translucent	-	-	4	-
base	-	crucible base fragment, thick grey with red glass, overlain by a think layer of cracked green glass.	-	opaque/ translucent	-	-	4	Vollgraff & van Hoorn 1934
rim	-	crucible rim fragment, thick grey - pink fabric with a thick layer of striped red and green glass. weathered areas and a white glassy material under the rim.	-	opaque/ translucent	-	x	4	Vollgraff & van Hoorn 1934

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Utrecht-Domplein	35	1933-zn2	?	?	-	-	production waste	crucible
Utrecht-Domplein	36	1933-77-84	?	?	-	-	production waste	crucible
Utrecht-Oudwijkerdwarsstraat	77	6-1-170	170	pit	-	-	production waste	undiagnostic
Utrecht-Oudwijkerdwarsstraat	78	5-1-135	135	pit	-	-	production waste	drop
Utrecht-Oudwijkerdwarsstraat	79	5-1-135	135	pit	-	-	vessel	sherd
Wijk bij Duurstede (Dorestad)	LM 16	-	-	-	-	-	vessel	lamp base
Wijk bij Duurstede (Dorestad)	LM 17	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM18	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 19	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 20	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 21	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 22	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 23	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 24	-	-	-	-	-	vessel	bowl
Wijk bij Duurstede (Dorestad)	LM 25	-	-	-	-	-	vessel	possible unguentarium
Wijk bij Duurstede (Dorestad)	LM 26	-	-	-	-	-	vessel	possible unguentarium/ bowl
Wijk bij Duurstede (Dorestad)	LM 27	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	LM 28	-	-	-	-	-	vessel	bell beaker
Wijk bij Duurstede (Dorestad)	LM 29	-	-	-	-	-	vessel	bell beaker
Wijk bij Duurstede (Dorestad)	LM 30	-	-	-	-	-	vessel	rim?beaker
Wijk bij Duurstede (Dorestad)	LM 31	-	-	-	-	-	vessel	rim?beaker
Wijk bij Duurstede (Dorestad)	LM 32	-	-	-	-	-	vessel	jar
Wijk bij Duurstede (Dorestad)	LM 33	-	-	-	-	-	vessel	trail decorated rim

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
rim	-	crucible rim, grey fabric with green glass and weathered surface.	-	translucent	-	x	4	Vollgraff & van Hoorn 1934
rim	-	crucible rim fragment (1 of 4), thin pitted pink-grey ceramic, green and red glass attached.	-	translucent/ opaque	-	-	4	-
undiagnostic	-	fragments (crushed?)	-	translucent	-	-	3	-
-	-	irregular drop, pale green modern	-	translucent	-	-	3	-
sherd	-	small green sherd	-	translucent	-	-	3	-
base	-	-	green	translucent	-	-	4	-
body	-	-	green	translucent	-	-	4	-
body	-	-	green	translucent	-	-	4	-
base	-	-	green	translucent	-	-	4	-
body	-	-	green	translucent	-	-	4	-
body	-	-	green	translucent	-	-	4	-
body	-	-	green	translucent	-	-	4	-
body	-	-	olive green	translucent	-	-	4	-
body	Isings 1957, type 24?	-	green	translucent	-	-	Roman	-
body	Isings 1957, type 10	-	green	translucent	-	-	Roman	-
body	Isings 1957, type 10 or 20	-	pale blue	translucent	-	-	Roman	-
body	-	-	green	translucent	-	-	4	-
body	-	-	green	translucent	-	-	3	-
body	-	-	green	translucent	-	-	3	-
rim	-	-	green	translucent	-	-	4?	-
rim	-	-	turquoise	translucent	-	-	4?	-
body	-	-	green	translucent	-	-	3	-
rim	-	-	turquoise	translucent	-	-	4	-

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Wijk bij Duurstede (Dorestad)	DOR 53	-	-	-	-	-	vessel	gold glass decorated ?beaker
Wijk bij Duurstede (Dorestad)	DOR 61	-	-	-	-	-	vessel	red trailed beaker
Wijk bij Duurstede (Dorestad)	DOR 66	-	-	-	-	-	vessel	blue rimmed beaker
Wijk bij Duurstede (Dorestad)	DOR 90	-	-	-	-	-	vessel	blue rimmed beaker
Wijk bij Duurstede (Dorestad)	DOR 91	-	-	-	-	-	vessel	sub-sample: body of 90
Wijk bij Duurstede (Dorestad)	DOR 96	-	-	-	-	-	vessel	beaker
Wijk bij Duurstede (Dorestad)	DOR 97	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 98	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 100	-	-	-	-	-	vessel	jar
Wijk bij Duurstede (Dorestad)	DOR 101	-	-	-	-	-	vessel	palm cup
Wijk bij Duurstede (Dorestad)	DOR 102	-	-	-	-	-	vessel	palm funnel series
Wijk bij Duurstede (Dorestad)	DOR 103	-	-	-	-	-	vessel	palm funnel series
Wijk bij Duurstede (Dorestad)	DOR 104	-	-	-	-	-	vessel	palm cup
Wijk bij Duurstede (Dorestad)	DOR 105	-	-	-	-	-	vessel	base
Wijk bij Duurstede (Dorestad)	DOR 106	-	-	-	-	-	vessel	palm cup or funnel
Wijk bij Duurstede (Dorestad)	DOR 107	-	-	-	-	-	vessel	palm cup
Wijk bij Duurstede (Dorestad)	DOR 108	-	-	-	-	-	vessel	palm cup
Wijk bij Duurstede (Dorestad)	DOR 109	-	-	-	-	-	vessel	palm cup
Wijk bij Duurstede (Dorestad)	DOR 110	-	-	-	-	-	vessel	palm funnel
Wijk bij Duurstede (Dorestad)	DOR 111	-	-	-	-	-	vessel	palm funnel
Wijk bij Duurstede (Dorestad)	DOR 112	-	-	-	-	-	vessel	palm funnel
Wijk bij Duurstede (Dorestad)	DOR 113	-	-	-	-	-	vessel	gold foil decoarted palm funnel
Wijk bij Duurstede (Dorestad)	DOR 115	-	-	-	-	-	vessel	funnel beaker base
Wijk bij Duurstede (Dorestad)	DOR 116	-	-	-	-	-	vessel	funnel beaker

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green or colourless	translucent	-	-	4	-
rim	-	-	pale green	translucent	-	-	4	-
rim	-	-	blue	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4?	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	mid green	translucent	-	-	4	-
body	-	-	yellow-green	translucent	-	-	4	-
body	-	-	mid green	translucent	-	-	3	-
base	-	-	red and colourless	opaque and transparent	-	-	4	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	3	-
body	-	-	pale green	translucent	-	-	4?	-
base	-	-	yellow-green iridescent	translucent	-	-	4	-
body	-	-	mid green	translucent	-	-	4	-

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Wijk bij Duurstede (Dorestad)	DOR 117	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 118	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 119	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 120	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 121	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 122	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 123	-	-	-	-	-	vessel	funnel beaker with bulge
Wijk bij Duurstede (Dorestad)	DOR 124	-	-	-	-	-	vessel	funnel beaker with bulge
Wijk bij Duurstede (Dorestad)	DOR 125	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 126	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 127	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 128	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 129a	-	-	-	-	-	vessel	vessel with applied blue thread
Wijk bij Duurstede (Dorestad)	DOR 129b	-	-	-	-	-	vessel	sub-sample thread decorating 129a
Wijk bij Duurstede (Dorestad)	DOR 130a	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 130b	-	-	-	-	-	vessel	vessel?
Wijk bij Duurstede (Dorestad)	DOR 131	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 132	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 133	-	-	-	-	-	vessel	?funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 134	-	-	-	-	-	vessel	vessel?
Wijk bij Duurstede (Dorestad)	DOR 135	-	-	-	-	-	vessel	beaker trail below tim
Wijk bij Duurstede (Dorestad)	DOR 136	-	-	-	-	-	vessel	funnel beaker base
Wijk bij Duurstede (Dorestad)	DOR 137	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 138	-	-	-	-	-	vessel	funnel beaker

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
body	-	-	acqua	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	colourless	transparent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	colourless	transparent	-	-	4	-
body	-	-	colourless	transparent	-	-	4	-
rim	-	-	pale green	translucent	-	-	4	-
rim	-	-	cobalt blue	translucent	-	-	4	-
body	-	-	blue	translucent	-	-	4	-
body	-	-	cobalt blue	translucent	-	-	4?	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	aqua mid green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	mid green	translucent	-	-	4?	-
rim	-	-	pale green	translucent	-	-	4	-
base	-	-	yellow-green	translucent	-	-	4	-
body	-	-	pale green	translucent	-	-	4	-
body	-	-	mid green	translucent	-	-	4	-

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Wijk bij Duurstede (Dorestad)	DOR 139	-	-	-	-	-	vessel	bowl
Wijk bij Duurstede (Dorestad)	DOR 140	-	-	-	-	-	vessel	funnel beaker
Wijk bij Duurstede (Dorestad)	DOR 141	-	-	-	-	-	vessel	funnel beaker applied cable
Wijk bij Duurstede (Dorestad)	DOR 142	-	-	-	-	-	vessel	funnel beaker trail decoarted
Wijk bij Duurstede (Dorestad)	DOR 143	-	-	-	-	-	raw chip	raw chip
Wijk bij Duurstede (Dorestad)	DOR 144	-	-	-	-	-	tessera	tessera
Wijk bij Duurstede (Dorestad)	DOR 145	-	-	-	-	-	tessera	tessera
Wijk bij Duurstede (Dorestad)	DOR 146	-	-	-	-	-	tessera	tessera
Wijk bij Duurstede (Dorestad)	DOR 147	-	-	-	-	-	tessera	tessera
Wijk bij Duurstede (Dorestad)	DOR 148	-	-	-	-	-	tessera	tessera
Wijk bij Duurstede (Dorestad)	DOR 149	-	-	-	-	-	rod	rod
Wijk bij Duurstede (Dorestad)	DOR 150	-	-	-	-	-	linen smoother	linen smoother
Wijk bij Duurstede (Dorestad)	DOR 151	-	-	-	-	-	linen smoother	linen smoother
Susteren	SUST 1	V12-053-GL-09	S12/067	water course 4310	800	1200	bead	annular
Susteren	SUST 2	V07-216-GL-01	S07/148	cistern	600	900	bead	biconical
Susteren	SUST 3	V09-205-GL-01	S09/200	posthole	700	1000	bead	conical
Susteren	SUST 4	V01-304-GL-01	S01/212	water course 4200	1000	1300	bead	conical
Susteren	SUST 5	V08-190-GL-17	S08/171	water course 4302	700	1000	bead	conical
Susteren	SUST 6	V04-245-GL-04	S04/244	water course 4250	1000	1350	bead	cylindrical
Susteren	SUST 7	V09-129-GL-01	S09/100	grave 58	900	1100	window	irregular
Susteren	SUST 8	V04-194-GL-01	S04/199	water course 4400	700	1200	window	triangle?
Susteren	SUST 9	V08-190-GL-10	S08/171	water course 4302	700	1000	window	trapezium
Susteren	SUST 10	V09-273-GL-01	S09/179	grave 67	800	900	window	leaf?

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
body	-	-	mid green	translucent	-	-	3 or 4	-
body	-	-	yellow green	translucent	-	-	4	-
rim	-	-	pale green	translucent	-	-	4	-
rim	-	-	pale green	translucent	-	-	4	-
chip	-	-	cobalt blue	translucent	-	-	4?	-
whole	-	-	cobalt blue	translucent	-	-	4?	-
whole	-	-	cobalt blue	translucent	-	-	4?	-
whole	-	-	turquoise	opaque	-	-	4?	-
whole	-	-	turquoise	opaque	-	-	4?	-
whole	-	-	opaque mid green	opaque	-	-	4?	-
incomplete	-	-	opaque yellow	opaque	-	-	4?	-
incomplete	-	-	dark green	translucent	-	-	4	-
incomplete	-	-	dark green	translucent	-	-	4	-
half	Koch 1977 Group O	-	black	translucent	3 white zigzags, 4 blue trails	-	1	-
complete	Callmer 1977 B546?	-	bluish green	translucent	3 yellow zigzags, 4 red trails	-	4?	-
complete	?	-	blue-green	translucent	yellow feather, 2 red trails	x	4?	-
half	?	-	bluish green	translucent	white feather, 2 yellow bands	x	4?	-
half	?	-	greenish	translucent	yellow festoons	x	4?	-
fragment	?	-	greenish	translucent	white and orange festoons, yellow bands	x	4?	-
complete?	-	-	dark blue	translucent	-	x	4?	-
complete?	-	-	dark blue	translucent	-	-	4?	-
almost complete	-	-	dark green	translucent	-	x	4?	-
almost complete	-	-	colourless	transparent	-	-	4?	-

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Susteren	SUST 11	V04-133-GL-01	S04/162	water course 4400	700	1200	window	rectangle?
Susteren	SUST 12	V08-138-GL-01	S08/155	water course 4302	700	1000	window	undiagnostic
Susteren	SUST 13	V06-158-GL-01	S06/150	water course 4200	700	1300	window	semi-circle
Susteren	SUST 14	V08-214-GL-01	S08/236	water course 4301	700	1000	window	undiagnostic
Susteren	SUST 15	V08-190-GL-12	S08/171	water course 4302	700	1000	window	undiagnostic
Susteren	SUST 16	V09-190-GL-11	S08/171	water course 4302	700	1000	window	undiagnostic
Susteren	SUST 17	V12-053-GL-10	S12/067	water course 4310	800	1200	production waste	crucible
Susteren	SUST 18	V12-053-GL-11	S12/067	water course 4310	800	1200	production waste	crucible
Susteren	SUST 19	V08-190-GL-02	S08/171	water course 4302	700	1000	vessel	funnel
Susteren	SUST 20	V08-190-GL-07	S08/171	water course 4302	700	1000	vessel	bowl
Susteren	SUST 21	V08-190-GL-03	S08/171	water course 4302	700	1000	vessel	funnel
Susteren	SUST 22	V05-194-GL-01	S05/219	water course 4400	700	1000	vessel	(palm)funnel
Susteren	SUST 23	V04-232-GL-01	S04/199	water course 4400	700	1200	vessel	funnel
Susteren	SUST 24	V04-166-GL-01	S04/171	water course 4302	700	1000	vessel	bowl
Susteren	SUST 25	V12-053-GL-01	S12/067	water course 4310	800	1200	vessel	funnel
Susteren	SUST 26	V08-219-GL-01	S08/218	pit	800	900/1000	vessel	funnel
Susteren	SUST 27	V12-053-GL-02	S12/053	water course 4310	800	1200	vessel	(palm)funnel
Susteren	SUST 28	V07-148-GL-01	S07/023	pit	900	1000	vessel	funnel
Susteren	SUST 29	V07-148-GL-02	S07/023	pit	900	1000	vessel	funnel
Deventer	DEV 1	434/16203	15050	cesspit 278	850	900	production waste	slag, hollow
Deventer	DEV 2	434/10479	11011	floor level 24	850	900	bead	globular
Deventer	DEV 3	434/99302	10239	cesspit 228	850	900	vessel	funnel
Deventer	DEV 4	434/99721	12507	cesspit 142	850	900	vessel	undiagnostic
Deventer	DEV 5	434/21098	12507	cesspit 142	850	900	vessel	undiagnostic
Deventer	DEV 6	434/99025	290	waste pit 56	850	900	vessel	funnel

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
almost complete	-	-	bluish green	translucent	-	xx	4?	-
fragment	-	-	bluish green	translucent	-	-	4?	-
complete	-	-	bluish green	translucent	-	x	4?	-
fragment	-	-	bluish green	translucent	-	x	4?	-
fragment	-	-	dark blue-green	translucent	-	-	4?	-
fragment	-	-	dark blue-green	translucent	-	-	4?	-
fragment	-	-	dark blue	translucent	-	xx	4?	-
fragment	-	-	light (bluish) green	translucent	-	-	4?	-
base	-	-	bluish green	translucent	-	xx	4	-
body	Lund Feveile 2006, rim type a	-	almost colourless	transparent	yellow reticella, spiral	x	4	-
rim	Lund Feveile 2006, rim type e	-	bluish green	transparent	-	-	4	-
base	-	-	bluish green	translucent	-	-	3/4	-
base	-	-	light blue-green	translucent	-	-	4	-
body	-	-	dark blue	translucent	yellow spiral	-	4	-
rim	Lund Feveile 2006, rim type d	-	yellow-green	translucent	-	-	4	-
rim	Lund Feveile 2006, rim type g	-	almost colourless	transparent	blue incalmo rim	-	4	-
base	-	-	blue-green	transparent	-	-	3/4	-
body	-	-	bluish green	transparent	white reticella	-	4	-
rim	Lund Feveile 2006, rim type e	-	light bluish green	translucent	-	-	4	-
complete	-	-	grey-green	opaque	-	-	5	-
complete	-	-	dark blue	translucent	-	-	5	-
body	-	-	bluish green	translucent	-	-	5	-
body	-	-	colourless		-	x	5	-
body	-	-	colourless	transparent	-	x	5	-
body	-	-	bluish green	translucent	optic blown ribs	-	5	-

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Deventer	DEV 7	434/99302	10239	cesspit 228	850	900	vessel	funnel?
Deventer	DEV 8	312/29024	21911	wastepit 60	900	925	bead	globular
Deventer	DEV 9	312/29064	22458	cesspit 74	900	925	undiagnostic	undiagnostic
Deventer	DEV 10	312/29089	22638	cesspit 74	900	925	vessel	funnel?
Deventer	DEV 11	312/29089	22638	cesspit 74	900	925	vessel	funnel?
Deventer	DEV 12	312/29090	22638	cesspit 74	900	925	vessel	funnel?
Deventer	DEV 13	434/12394	12765	cesspit 235	900	900	vessel	funnel/conical beaker?
Deventer	DEV 14	312/29028	21911	wastepit 60	900	925	vessel	undiagnostic
Deventer	DEV 15	312/29028	21911	wastepit 60	900	925	production waste	raw glass
Deventer	DEV 16	312/29090	22638	cesspit 74	900	925	window	window
Deventer	DEV 17	312/29057	22457	cesspit 74	900	925	production waste	raw glass
Deventer	DEV 18	312/29028	21911	wastepit 60	900	925	production waste?	undiagnostic (trail?)
Deventer	DEV 19	434/10380	10879	layer 19	900	950	vessel	funnel
Deventer	DEV 20	434/99116	2301	wastepit 107	900	950	vessel	cup
Deventer	DEV 21	434/99144	2538	wastepit 174	900	950	production waste	raw glass
Deventer	DEV 22	434/99289	6623	house 9	900	950	vessel	beaker?
Deventer	DEV 23	434/99289	6623	house 9	900	950	vessel	undiagnostic
Deventer	DEV 24	434/99598	7160	cesspit 130	900	950	window	window
Deventer	DEV 25	434/99578	7120	cesspit 128	925	950	vessel	funnel/beaker?
Deventer	DEV 26	434/99139	2535	cesspit 172	900	950	window	window?
Deventer	DEV 27	434/99154	2583	cesspit 116	900	950	production waste	raw glass
Deventer	DEV 28	434/10638	11039	cesspit 256	890	925	vessel	funnel?
Deventer	DEV 29	434/99154	2583	cesspit 116	900	950	production waste	raw glass
Deventer	DEV 30a	434/7682	7214	cesspit 133	900	950	vessel	bottle?
Deventer	DEV 30b	434/7682	7214	cesspit 133	900	950	vessel	bottle?
Deventer	DEV 31	312/20975	20356	wastepit 30	900	950	window?	window
Deventer	DEV 32	312/22981	20765	wastepit 39	950	1000	window	window
Deventer	DEV 33	312/22985	20765	wastepit 39	950	1000	window	window
Deventer	DEV 34	312/22986	20765	wastepit 39	950	1000	bead?	undiagnostic
Deventer	DEV 35	434/99423	14377	cesspit 327	950	1050	vessel	undiagnostic
Deventer	DEV 36	434/99923	15616	cesspit 286	950	1050	vessel	undiagnostic

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
rim	-	-	light green	translucent	-	x	5	-
complete	-	-	light blue-green	translucent	-	x	5	-
splinter	-	-	yellow-brown	translucent	-	-	5	-
rim	-	-	blue-green	translucent	opaque white spiral	-	5	-
rim	-	-	blue-green	translucent	-	-	5	-
rim	-	-	light bluish green	translucent	-	-	5	-
body	-	-	bluish green	translucent	-	-	5	-
body/base	-	-	undiagnostic	?	-	xxx	5	-
chip?	-	-	undiagnostic	?	-	xxx	5	-
fragment	-	-	-	?		xxx	5	-
chip?	-	-	undiagnostic	?	-	xxx	5	-
fragment	-	-	bluish green	translucent	-	-	5	-
body	-	-	bluish green	translucent	optic blown ribs	-	5	-
rim	Isings 1957, type 96a	-	yellow-green	translucent	-	x	5	-
chunk	-	-	bluish green	translucent	-	-	5	-
body	-	-	colourless	transparent	self-coloured trail	x	5	-
body, curved	-	-	pale pink	translucent	-	xx crizzled	5	-
fragment	-	-	pale blue-green	translucent	-	xx	5	-
body	-	-	colourless	transparent	2 white trails	-	5	-
fragment	-	-	deep turquoise	translucent	-	xx	5	-
chip	-	-	light green	translucent	-	xx	5	-
body	-	-	yellowish green	translucent	-	xx	5	-
chip	-	-	bluish green	translucent	-	xx	5	-
neck?	-	-	pale green	translucent	-	xx	5	-
neck?	-	-	red purple streak	translucent	-	xx	5	-
fragment	-	-	blue-green	translucent	-	-	5	-
fragment	-	-	green?	?	-	xx	5	-
fragment	-	-	green?	?	-	xxx	5	-
fragment	-	-	amber	translucent	-	-	5	-
rim, thick	-	-	greenish	translucent	-	xxx	5	-
body	-	-	greenish	translucent	-	xx	5	-

Appendix I sample list

Site	Sample	Find number	Feature number	Feature type	Begin date feature (AD)	End date feature (AD)	Category object	Form/object
Deventer	DEV 37	434/12362	12915	house 12	950	1050	vessel	funnel?
Deventer	DEV 38	434/99923	15616	cesspit 286	950	1050	window	window
Deventer	DEV 39	312/20678	20306	wastepit 34	950	1050	window	window
Deventer	DEV 40a	312/29048	22270	cesspit 80	950	1050	production waste?	melted, 2 layers
Deventer	DEV 40b	312/29048	22270	cesspit 80	950	1050	production waste?	melted, 2 layers
Deventer	DEV 41	312/29063	22425	layer 8	950	1050	window?	window/inlay?

Key weathering x=slightly weathered xx = moderately weathered xxx= badly weathered
Key archaeological periods 1= 450-550 AD 2= 550-650 AD 3= 650-750 AD 4= 750-850 AD 5= 850-1000 AD

Type of fragment	Typology (Isings, Koch, Callmer, Ribe or Pion)	Description object	Colour	Transparancy	Decoration	Weathering	Archeological period	Publication
body	-	-	light blue-green	translucent	-	x	5	-
rectangle?	-	-	bluish green	translucent	-	x	5	-
fragment	-	-	greenish	translucent	-	xx	5	-
chip	-	-	red	opaque	-	-	5	-
chip	-	-	turquoise	translucent	-	-	5	-
fragment	-	-	turquoise	translucent	-	-	5	-

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
Gennep glass samples								
GE 41	13.69	0.86	2.68	67.89	0.08	0.33	-	0.76
GE 42	15.23	0.85	2.97	68.84	-	0.4	-	0.54
GE 43	15.18	0.77	2.94	69.55	0.03	0.37	-	0.43
GE 44	15.38	1	3.37	71.06	-	0.32	-	0.44
GE 45	14.74	0.98	3.1	68.21	0.05	0.31	-	0.55
GE 46	14.98	0.78	2.87	68.99	-	0.35	-	0.44
GE 47	15.91	0.62	2.7	74.73	-	0.33	-	0.69
GE 48	13.63	0.77	2.91	71.17	0.05	0.37	-	0.72
GE 49	14.34	0.85	2.91	70.65	-	0.36	-	0.76
GE 51	13.93	0.94	2.94	70.37	0.02	0.34	-	0.72
GE 52	14.44	0.89	2.4	70.83	0.01	0.33	-	0.56
GE 53	15.1	0.73	2.7	71.4	-	0.4	-	0.68
GE 54	15.85	1.11	2.81	67.76	0.01	0.42	-	0.61
GE 55	16.15	1.11	2.9	67.59	0.05	0.42	-	0.6
GE 56	16.36	1.22	2.8	70.4	-	0.31	-	0.41
GE57	14.04	0.92	2.84	68.36	-	0.41	-	0.86
GE 58	13.97	1	3.01	68.04	0.03	0.42	-	0.8
GE 59	15.86	0.99	2.77	68.66	0.01	0.44	-	0.68
GE 60	16.12	1.19	2.93	66.78	0.04	0.46	-	0.69
GE 61	13.78	0.69	2.74	72.39	0.01	0.26	-	0.72
GE 62	14.39	0.78	2.88	70.89	0.06	0.29	-	0.71
GE 63	13.6	0.68	2.85	72.72	0.01	0.23	-	0.73
GE 64	14.15	0.76	2.96	70.94	0.04	0.26	-	0.81
GE 65	15.05	0.74	2.86	71.65	-	0.3	-	0.61
GE 66	14.19	0.82	2.99	72.26	0.01	0.26	-	0.57
GE 67	14.57	0.83	2.85	72.54	0.02	0.27	-	0.61
GE 68	12.36	0.69	2.93	73.37	-	0.25	-	0.74
GE 69	14.95	1.04	3.02	71.02	-	0.25	-	0.42
Maastricht-Jodenstraat (MAJO) glass samples								
Joden 1	11.77	1.15	2.43	53.26	0.13	0.31	0.63	0.62
Joden 2	12.43	1.01	2.44	60.89	0.15	0.24	0.64	0.72
Joden 3	16.42	1.21	2.56	67.05	0.09	0.35	0.79	0.57
Joden 4	14.1	1.13	2.67	64.19	0.15	0.33	0.78	0.44
Joden 5	14.49	1.24	2.79	62.07	0.18	0.27	0.8	0.47
Joden 6	10.49	0.92	2.23	58.09	0.19	0.23	0.67	0.48
Joden 37	16.04	0.72	2.25	69.97	0.05	0.34	0.96	0.55
Joden 38	17.03	0.88	2.35	70.36	0.1	0.39	0.84	0.44
Joden 39	16.54	0.76	2.35	70.14	0.05	0.31	0.95	0.46
Joden 40	16.87	0.73	2.26	71.34	0.02	0.3	1	0.3
Joden 41	15.49	1.14	2.6	62.42	0.18	0.22	0.7	0.84
Joden 42	14.15	0.72	2.38	61.92	0.1	0.23	0.84	0.66
Joden 43	16.14	1.16	2.58	61.94	0.2	0.25	0.66	0.87

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
7.42	0.12	0.84	1.49	0.01	0.66	-	0.53	2.99	100.41
7.43	0.32	1.53	2.14	-	0.19	0.02	0.13	0.35	101.04
6.94	0.31	2.26	2.04	0.03	0.02	0.03	-	0.02	100.97
6.44	0.32	1.59	1.99	0.04	0.04	-	0.03	0.06	102.16
7.75	0.31	2.4	1.99	-	0.06	-	0	0.11	100.6
6.76	0.31	2.25	1.61	-	0.03	-	-	0.02	99.47
7.6	0.11	0.93	0.6	-	0.35	0.02	0.03	0.04	104.74
8.2	0.16	0.53	0.92	0.04	0.18	‘-	0.03	0.21	99.9
8.58	0.2	1.03	0.95	-	0.15	0	0.12	0.38	101.37
7.33	0.19	1.06	1.26	-	0.54	0.01	0.41	1.37	101.48
7.07	0.16	0.86	1.14	0.01	0.36	-	0.29	1.51	100.96
8.18	0.14	1.52	0.69	0.02	0.08	0.04	0.06	0.09	101.9
8.84	0.14	1.49	0.68	-	0.08	-	-	-	99.88
8.9	0.18	1.51	0.78	-	0.09	-	-	0.02	100.32
6.98	0.25	1.78	0.86	0	0.01	0.01	-	0	101.44
9.2	0.15	1.4	0.92	-	0.08	-	-	0.08	99.35
9.23	0.18	1.34	1.09	0.03	0.08	-	-	0.02	99.28
9.06	0.15	1.3	0.85	-	0.07	-	0.04	0.01	100.96
9.46	0.15	1.54	0.86	0	0.08	-	-	0.03	100.37
7.79	0.09	0.66	0.73	-	0.27	-	0.02	0.06	100.28
7.67	0.15	0.98	0.78	-	0.19	0.01	0.02	0.14	99.96
7.6	0.11	0.9	0.6	-	0.24	-	-	0.09	100.43
7.84	0.13	0.99	0.84	0.02	0.14	0.01	0.04	0.2	100.17
7.05	0.16	1.09	0.8	0.02	0.23	-	0.08	0.39	101.1
7.67	0.15	0.95	0.8	0.02	0.15	0.01	0.01	0.09	101.01
7.44	0.17	1.11	0.75	-	0.14	-	0.06	0.1	101.5
8.28	0.1	0.74	0.64	-	0.15	0	0.02	0.07	100.45
6.32	0.42	1.96	1.23	-	0.02	0.01	0.03	0.04	100.78
5.11	0.11	1.21	2.66	0.01	-	0.65	0.45	7.13	87.61
6.53	0.12	1.18	2.51	0.01	-	0.63	0.58	6.13	96.22
7.07	0.12	1.5	0.79	-	-	0.53	-	0.37	99.42
6.41	0.16	1.45	1.24	-	-	3.08	0.2	4.8	101.12
6.26	0.19	1.63	1.39	-	-	2.86	-	4.69	99.32
5.25	0.09	1.36	0.71	-	-	1.72	-	19.16	101.58
5.55	0.1	0.05	0.86	0.01	-	0.18	0.02	0.67	98.31
6.18	0.12	0.13	0.57	0.01	-	-	0.02	0.27	99.69
5.62	0.11	0.04	0.56	-	0.07	-	-	0.3	98.27
5.42	0.11	0.06	0.68	0.02	-	-	-	0.53	99.64
6.9	0.14	1.27	1.3	-	0.04	0.14	1.54	3.13	98.03
6.28	0.1	0.69	1.55	-	0.2	0.17	1.7	7.32	99
6.74	0.14	1.45	0.86	0.01	-	0.59	2.77	0.71	97.08

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
Joden 44	19.39	1.45	2.62	63.2	0.18	0.28	0.88	0.78
Joden 45	16.58	0.95	2.65	66.86	0.22	0.22	0.87	0.65
Joden 46	17.46	0.99	2.68	65.6	0.05	0.21	0.97	0.43
Joden 47	11.07	0.83	2.17	47.47	0.17	0.17	0.44	0.54
Joden 48	15.82	1.1	2.68	63.17	0.14	0.24	0.78	0.88
Joden 49	16.84	1.22	2.65	64.27	0.17	0.31	0.83	0.97
Joden 50	12.05	1.18	2.25	56.27	0.13	0.3	0.67	7.99
Joden 51	12.65	1.17	2.38	54.17	0.16	0.28	0.67	0.64
Joden 52	16	1.18	2.37	58.7	0.19	0.36	0.66	0.79
Joden 53	14.31	0.72	2.57	70.63	0.07	0.2	0.88	0.4
Joden 54	12.14	1.08	2.52	56.33	0.2	0.29	0.71	0.69
Joden 55	9.66	0.74	2	38.02	0.14	0.17	0.37	1.69
Joden 56	10.53	0.96	2.09	44.95	0.12	0.21	0.56	0.46
Joden 57	13.1	1	2.39	60.96	0.17	0.26	0.75	0.64
Joden 58	14.88	1.2	2.45	60.2	0.19	0.34	0.78	0.49
Joden 59	15.05	1.11	2.53	61.74	0.18	0.29	0.78	0.72
Joden 60	16.81	0.8	2.72	67.87	0.21	0.14	0.77	0.84
Joden 61	15.49	0.72	2.38	69.34	0.14	0.26	0.92	0.58
Joden 62	16.14	1.29	2.64	67.06	0.13	0.31	0.73	0.93
Joden 63	16.76	1.55	2.67	64.02	0.18	0.34	0.76	1.77
Joden 64	9.8	0.72	1.89	39.52	0.06	0.15	0.46	0.32
Joden 65	9.96	0.86	1.91	37.42	-	0.09	0.42	0.41
Joden 66	11.7	1.02	2.49	55.59	0.17	0.25	0.64	0.74
Joden 67	14.48	1.04	2.42	61.18	0.15	0.23	0.69	0.78
Joden 68	15.95	0.52	2.53	69.67	0.14	0.17	1.04	0.58
Joden 69	10.01	0.83	2.17	47.3	0.2	0.22	0.49	0.37
Joden 70	11.24	1.06	2.36	56.05	0.16	0.25	0.61	0.53
Joden 71	10.41	0.9	2.29	46.31	0.19	0.19	0.57	0.58
Joden 72	10.8	0.88	2.18	50.67	0.15	0.24	0.69	0.5
Joden 73	14.28	1.28	2.38	60.58	0.14	0.31	0.76	0.74
Joden 74	14.8	1.26	2.4	59.42	0.28	0.34	0.77	0.74
Joden 75	13.08	0.9	2.38	58.4	0.15	0.23	0.67	0.66
Joden 76	14.26	1.3	2.44	58.18	0.2	0.31	0.69	0.73
Maastricht-Jodenstraat (MAJO) crucibles								
Joden 19 (lead glass)	0.31	0.35	4.07	24.57	0.1	0.69	-	1.01
Joden19 (yellow residue)	0.62	0.54	8.15	27.46	0.14	0	0.01	1.62
Joden 20 (lead glass)	0.41	0.68	2.53	22.74	0.03	0.07	0.1	1.03
Joden 20 (yellow residue)	0.406	0.675	2.533	22.737	0.1	-	0.029	1.034
Joden 21 (natron glass)	12.29	0.91	10.56	69.24	0.13	0.07	0.18	2.49
Joden 22 (lead glass)	0.26	0.59	4.39	26.65	0.21	0.17	0.04	0.85
Joden 23 (white melt)	0.11	0.39	2.47	12.45	0.04	0.04	-	-

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
7.61	0.16	1.9	0.66	-	0	-	-	0.05	99.16
6.91	0.14	1.02	0.95	-	0.08	-	0.08	0.02	98.21
5.85	0.34	1.67	1.08	0.03	0.04	-	0.12	-	97.52
5.14	0.15	0.98	0.96	0.01	-	3.71	-	23.75	97.55
6.29	0.16	1.35	0.79	0.02	0.03	0.31	1.84	3.14	98.72
7.43	0.15	1.55	0.84	0.07	0.1	-	0.08	0.04	97.54
4.11	0.15	1.31	0.99	-	-	1.16	0.12	2.48	91.15
5.02	0.11	1.22	2.19	0.05	-	0.81	0.75	8.63	90.9
6.59	0.12	1.36	0.78	0.05	-	0.17	4.16	0.27	93.74
4.86	0.14	0.05	0.74	0.04	0.03	0.05	0.17	0.62	96.48
5.74	0.13	1.24	3.94	-	-	1.5	1.1	7.69	95.31
3.16	0.1	0.87	1.96	0.06	-	1.02	0.36	36.54	96.86
5.5	0.11	1.13	0.9	0.02	-	3.13	0.07	26.27	96.99
7.42	0.14	1.22	0.72	0.05	-	0.24	2.64	3.71	95.42
5.96	0.12	1.59	0.7	0.02	-	5.68	0.07	2.21	96.89
6.53	0.13	1.56	0.8	0.07	-	2.12	0.08	3.13	96.81
6.63	0.15	0.68	0.8	0.01	0.21	-	0.11	0.35	99.11
5.89	0.09	0.41	0.74	0.04	1.72	-	0.15	0.33	99.19
7.53	0.16	1.76	0.73	0.02	0.06	-	0	-	99.48
7.96	0.16	1.8	0.78	-	0.09	-	-	-	98.85
3.05	0.09	0.87	0.7	-	-	3.04	0	42.07	102.75
2.82	0.09	0.59	0.56	0.01	-	1.71	-	27.16	84
5.69	0.14	1.44	2.7	-	-	1.57	1.42	10.78	96.35
6.65	0.17	1.29	2.55	-	0.1	0.13	2.33	3.27	97.44
6.92	0.07	0.46	0.42	0.03	0.12	-	0.08	0.08	98.8
4.27	0.09	0.86	1.07	0.01	-	3.8	0.01	24.46	96.15
5.58	0.14	1.1	0.89	-	-	1.77	0.01	17.23	98.98
4.98	0.08	1.01	1.25	0.07	-	2.81	0.09	26.72	98.44
4.95	0.12	1.37	0.7	-	-	1.46	0.04	24.48	99.22
8.23	0.13	1.58	0.84	0.06	-	0.28	2.57	3.96	98.13
7.23	0.14	1.64	0.89	0.08	-	1.8	2.89	4.2	98.88
8.83	0.11	1.09	0.84	0.03	-	0.67	2.59	5.86	96.48
6.88	0.12	1.47	0.82	-	0.03	0.39	2.47	3.9	94.19
0.68	0.26	0.01	1.55	-	-	0.49	0.06	61.53	95.66
3.84	0.51	0.04	2.43	0.03	-	9.48	-	42.98	97.84
0.86	0.27	0.05	2.48	-	-	0.54	-	62.48	94.26
0.86	0.272	0.051	0.483	0.028	-	9.536	-	62.477	101.22
2.17	0.48	0.33	3.17	0.02	0.03	-	-	-	102.07
1.64	0.24	0.05	1.5	0	0.06	1	0.1	56	93.74
0.54	0.11	0.01	0.87	-	-	61.58	0.01	22.83	101.45

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
Joden 25 (lead glass)	0.15	0.67	6.24	28.15	0.03	-	0.05	0.84
Joden 27 (lead glass)	0.28	0.44	3.44	35.43	0.17	0.01	0.03	1.38
Joden 27 (yellow residue)	0.05	0.05	1.05	11.12	0.25	0.01	0.04	-
Joden 28 (lead glass)	0.31	0.34	4.26	25.04	0.07	0.7	0.05	0.95
Joden 28 (yellow residue)	0.09	0.15	1.71	15.39	0.03	-	0.05	-
Joden 29 (natron glass)	17.08	1.1	3.24	67.71	0.16	0.24	0.65	1.02
Joden 30 (white melt)	0.49	0.36	2.18	19.78	0.02	-	0.01	-
Maastricht-Mabro crucibles								
Mabro 7	9.87	1.33	7.24	65.88	0.38	0.06	0.04	7.17
Mabro 8	15.79	0.72	9.87	69.38	0.08	0.13	0.38	0.85
Mabro 9	3.49	0.98	7.54	67.21	0.18	0.03	-	13
Mabro 10	12.43	1.49	2.74	65.69	0.24	0.11	0.01	2.99
Mabro 11	11.2	0.82	12.48	62.9	0.16	0.05	0.01	2.99
Mabro 12	0.02	0.25	0.65	15.64	0.06	-	0.06	0.84
Mabro 13	13.46	1.21	3.57	69.98	0.21	0.18	0.52	2.36
Mabro 14	0.49	0.59	6.27	28.43	0.09	-	0.05	0.86
Mabro 15	11.64	1.65	2.76	69.88	0.27	0.12	0.05	2.62
Mabro 16	16.67	0.99	3.48	68.99	0.1	0.19	0.38	1.27
Wijnaldum glass samples								
WIJ1	16.97	0.92	2.57	69.16	0.1	0.26	0.79	0.73
WIJ2	17.69	0.95	2.62	68.26	0.1	0.23	0.92	0.74
WIJ3	16.44	0.94	2.69	68.43	0.13	0.28	0.78	0.85
WIJ4	10.24	0.23	1.03	40.69	0.01	0.13	0.72	0.19
WIJ5	10.86	0.89	2.39	37.21	0.11	0.15	0.41	0.57
WIJ6	10.76	0.73	2.18	39.23	0.11	0.14	0.48	0.45
WIJ 7	9.29	1.21	1.86	38.89	0.24	0.15	0.22	0.95
WIJ 8	8.72	0.38	2.35	40.37	0.09	0.01	0.48	0.4
WIJ 9	6.96	0.3	2.24	35.31	0.04	0.01	0.42	0.31
WIJ 10	14.93	0.71	2.47	68.16	0.11	0.12	1	0.61
WIJ 11	16.48	0.95	2.57	69.18	0.16	0.21	0.73	1.14
WIJ 12	15.99	0.88	2.65	70.57	0.11	0.22	0.99	0.77
WIJ 13	16.46	0.74	2.55	71.35	0.09	0.18	0.98	0.62
WIJ 14	7.05	0.46	1.97	26.42	0.07	0.11	0.37	0.39
WIJ 15	14.65	0.64	2.57	69.7	0.14	0.1	1	0.41
WIJ 16 low lead	15.72	0.84	2.79	69.24	0.16	0.19	0.83	0.91
WIJ 16 high lead	10.98	0.48	1.9	44.92	0.09	0.12	0.52	0.51
WIJ 17	6.58	0.58	4.13	48.65	0.34	0.03	0.27	1.23
WIJ 18	13.37	1.07	2.79	59.73	0.2	0.22	0.76	0.91
WIJ 19	13.5	1.28	2.78	58.87	0.21	0.3	0.88	2.69
WIJ 20	14.87	1.45	2.76	61	0.29	0.26	0.74	1.11
WIJ 21	15.01	1.42	2.74	64.76	0.23	0.29	0.92	0.79

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
0.34	0.23	0	2.2	0.02	-	0.47	0.12	55.03	94.55
1.36	0.21	0.03	1.64	0.02	-	0.44	0.09	51.62	96.58
0.3	0.25	0.02	0.52	0	-	23.03	0.04	65.34	102.06
0.77	0.24	-	1.61	-	-	0.75	-	60.24	95.33
0.25	0.16	0.03	0.46	0.01	-	17.85	0.09	59.97	96.24
7.23	0.18	1.34	0.91	0.01	0.05	-	0.21	0.1	101.22
0.76	0.12	0.02	0.78	0.01	-	55.81	0.49	22.5	103.33
4.95	0.33	0.55	2.65	0	0.2	-	-	-	100.66
2.44	0.38	0.09	2.22	0.01	0.02	-	0.08	0.05	102.48
-	0.52	0.1	2.71	0.15	0.56	-	0.01	-	96.46
7.58	0.18	0.38	1.17	0.01	0.17	-	0.11	-	95.29
2.52	1.36	0.7	4.79	-	0.11	-	0.02	0.09	100.19
0.47	0.29	0.09	1.16	0.01	-	12.75	0.27	59.24	91.8
6.74	0.23	0.39	0.99	0	0.15	-	0.36	0.08	100.43
0.66	0.31	0.06	2.48	0.01	-	1.1	0.1	53.77	95.26
7.52	0.14	0.43	1.16	-	0.11	-	0.03	0.05	98.42
5.82	0.25	1.05	1.17	-	0.04	-	-	0.05	100.45
7.15	0.15	1.04	0.85	0.02	0.13	0.01	0.1	0.15	101.1
7.07	0.16	1.18	0.9	0.02	0.14	0.03	0.05	0.17	101.22
7.79	0.18	1.07	0.99	0.01	0.1	0.06	0.14	0.18	101.05
2.76	0.04	0.01	0.3	0	-	4.85	-	40.26	101.47
3.41	0.11	0.33	1.32	0.01	-	3.69	0.05	38.82	100.32
3.39	0.12	0.33	0.91	0	-	5.12	0.06	36.76	100.77
5.72	0.15	1.1	1.27	0.03	-	3.11	-	36.64	100.83
3.76	0.08	0.01	0.53	0.02	-	5.11	0.09	36.84	99.23
2.76	0.06	0.02	0.43	0.03	-	6.18	0.06	44.35	99.47
9	0.27	0.2	0.82	0.02	0.07	-	0.13	0.02	98.64
6.93	0.17	0.83	0.77	0.02	0.31	-	0.14	0.17	100.76
6.6	0.18	0.98	0.79	0.01	0.28	-	0.1	0.23	101.34
7.02	0.11	0.93	0.64	0	0.39	-	0	0.1	102.18
1.81	0.1	0.04	0.83	0.01	-	4.86	0.15	56.58	101.23
9.48	0.29	0.23	1.21	0.13	0.02	0	0.11	0.11	100.81
7.38	0.1	0.54	1.05	0.02	0.35	0	0.38	0.37	100.86
4.29	0.07	0.41	0.75	0.02	-	2.38	0.15	33.93	101.53
2.69	0.29	1.72	7.46	0	-	0.14	1.81	23.21	99.12
5.99	0.16	1.12	4.36	0.03	-	0.79	1.99	6.62	100.11
5.49	0.17	0.27	3.84	0.04	-	1	1.02	7.61	99.96
7.23	0.18	1.25	5.63	0.02	-	0.7	0.57	2.89	100.93
6.55	0.14	1.29	2.7	0.01	-	0.98	-	1.49	99.32

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
WIJ 22	14.07	0.69	2.5	67.49	0.13	0.18	0.95	0.51
WIJ 23	16.18	1.57	2.49	68.22	0.25	0.27	0.81	1.03
WIJ 24	11.23	0.98	2.49	51.57	0.15	0.2	0.7	0.56
WIJ 25	15.05	1.25	2.39	62.26	0.22	0.27	0.79	1.5
WIJ 26	17.07	1.25	2.67	63.85	0.17	0.38	0.83	0.78
WIJ 27	13.38	1.59	3.7	62.36	0.2	0.26	0.77	1.01
WIJ 28	14.09	1.32	2.97	59.2	0.26	0.33	0.76	0.95
WIJ 29	13.16	2.14	2.12	52.46	0.77	0.47	0.63	1.71
WIJ 30	14.47	1.33	2.29	62.44	0.22	0.21	0.78	0.88
WIJ 31	15.09	1.43	3.59	62.15	0.18	0.28	0.81	0.97
WIJ 32	11.1	0.64	2.08	45.68	0.1	0.21	0.66	0.51
WIJ 33	9.9	0.55	1.89	33.09	0.09	0.14	0.41	0.38
WIJ 34	0.24	0.19	6.26	35.54	0.5	0.01	0.01	1.66
WIJ 35	12.67	5.45	1.38	70.23	0.11	0.07	0.57	2.42
WIJ 36	17.07	1.31	2.72	65.1	0.17	0.28	0.91	0.71
WIJ 37	12.18	5.43	1.19	70.77	0.09	0.23	0.64	2.33
WIJ 38	16.01	1.11	2.65	69.88	0.07	0.31	0.55	0.62
WIJ 39 low lead	16.76	1.24	2.79	66.28	0.2	0.29	0.53	1.05
WIJ 39 high lead	11.07	1.2	2.78	58.87	0.4	0.22	0.54	1.19
WIJ 40	11.19	0.52	2.19	63.51	0.06	0.23	0.88	0.47
WIJ 41	16.97	1	2.82	67.28	0.15	0.23	0.93	0.68
WIJ 42	15.21	0.86	3.15	66.88	0.06	0.13	0.92	0.39
Wijk bij Duurstede (Dorestad) glass samples								
LM 25	16.85	0.66	2.55	70.62	0.1	0.2	0.99	0.75
LM 26	16.87	0.72	2.77	66.61	0.17	0.27	0.86	0.74
LM 27	15.02	0.67	2.34	65.33	0.14	0.23	0.61	1.04
LM 28	16.71	0.71	2.49	67.94	0.08	0.26	0.91	0.73
LM 29	15.44	0.8	2.42	68.03	0.14	0.24	0.87	0.93
LM 30	15.37	1.15	2.37	68.57	0.05	1.14	-	1.4
LM 31	16.21	0.79	2.39	68.51	0.06	1.12	-	1.14
LM 33	15.54	0.92	2.75	67.2	0.02	1.17	0.01	1.03
DOR 53	17.01	0.73	2.63	69.39	0.13	0.18	0.85	0.89
DOR 61	16.44	0.79	2.85	68.86	0.16	0.17	0.79	0.87
DOR 66	17.72	0.67	2.34	71.22	0.03	1.23	-	0.54
DOR 90	15.95	0.77	2.61	68.89	0.01	1.19	0.04	1.1
DOR 91	18.09	0.61	2.48	70.9	0.02	0.28	-	0
DOR 95	1.3	1.53	12.35	64.2	0.25	0.01	-	4.32
DOR 100	15.62	0.64	2.9	70.82	0.03	1.12	0.01	1.09
DOR 101	16.4	0.69	2.66	71.25	0.07	1.25	0.01	0.83
DOR 102	15.7	0.66	2.61	71.92	-	1.25	-	0.91
DOR 103	1.48	7.14	2.37	61.68	0.01	0.99	0.01	8.56

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
0.58	0.08	0.56	0.85	0.01	-	3.44	0.02	3.19	95.25
0.32	0.18	0.63	0.97	0.02	-	1.7	0.02	1.06	95.7
0.3	0.14	1.29	1.43	0.02	-	1.56	-	23.37	95.99
6.18	0.16	1.24	2.04	-	-	1.51	-	5.12	99.99
6.42	0.1	1.27	1.78	0.01	-	0.54	0.14	3.62	100.87
6.05	0.17	0.55	3.81	0.02	-	0.11	1.57	4.22	99.77
6.38	0.14	0.61	4.09	0.01	-	0.27	2.45	5.64	99.46
8.44	0.17	0.22	3.32	0.01	1.57	0.63	11.39	1.75	100.95
5.85	0.21	0.89	3.9	0.01	0.03	0.03	2.22	3.9	99.66
6.09	0.21	0.51	3.62	-	0.01	-	1.12	4.3	100.36
3.61	0.07	0.21	0.86	-	-	2.41	-	32.37	100.51
2.22	0.13	0.09	0.83	-	-	3.26	0.28	46.8	100.04
0.22	0.41	4.24	9.09	0.04	0.01	0.17	0.25	40.15	98.97
6.64	0.1	0.64	0.6	0.01	0.1	-	-	0.05	101.05
9.19	0.16	1.85	1.29	0.01	0.05	-	0.11	-	100.93
6.21	0.02	0.64	0.42	-	0.08	-	0.01	0.02	100.25
7.97	0.14	0.49	0.86	0.02	0.04	-	0.02	-	100.72
8.65	0.11	1.09	0.94	0.04	0.04	-	0.16	0.29	100.46
6.1	0.22	1.1	1.56	0.02	-	3.25	1.85	8.29	98.67
3.86	0.11	0.52	1.81	-	1.33	-	-	13.27	99.94
6.65	0.29	1.13	1.35	0	0.26	-	0.06	0.36	100.16
8.89	0.08	0.03	0.45	0.03	0.01	0.01	2.26	1.61	100.96
6.61	0.12	0.66	0.59	-	0.48	-	-	-	101.18
8.66	0.13	0.59	0.73	0.02	0.29	-	0.34	0.32	100.08
7.03	0.14	-	0.01	0	0.29	0.02	0	0.39	93.26
6.64	0.11	-	-	0.01	0.32	0.01	-	0.27	97.17
7.81	0.15	0.01	0.01	0	0.16	-	-	0.26	97.26
7.44	0.11	-	0.73	0.05	0.64	-	0.11	-	99.11
6.54	0.11	0.06	0.54	0.01	0.21	-	1.25	-	98.93
7.07	0.21	-	0.87	0.01	0.17	-	2.24	-	99.2
7.25	0.15	0.67	0.67	-	0.41	-	0.07	0.24	101.26
7.46	0.15	0.61	0.84	-	0.33	0.02	0.16	0.69	101.19
5.94	0.1	0.02	0.51	-	0.52	-	0.04	1.26	102.13
7.28	0.15	-	0.79	0.02	0.22	0	0.37	-	99.41
5.99	0.12	-	0.6	0.03	0.58	0.03	0.02	1.19	100.93
2.78	0.55	0.06	11.94	0.02	0.2	-	0.1	0.02	99.65
7.2	0.14	-	0.89	0.04	0.3	-	0.16	0.31	101.27
6.65	0.12	-	0.85	0.03	0.62	-	0.33	0.49	102.26
6.82	0.13	-	0.91	-	0.37	-	0.11	0.03	101.42
13.65	0.18	-	0.71	0.04	0.33	-	-	-	97.16

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
DOR 104	15.86	0.71	2.86	71.87	-	1.21	0.01	1.01
DOR 105 colourless	15.94	1.11	2.66	68.89	0.03	1.19	0.01	1.11
DOR 105 op red	15	0.64	2.73	68.24	0.06	1.18	-	0.91
DOR 106	16.28	0.62	2.82	71.63	0.01	1.26	0.02	0.81
DOR 107	16	0.82	2.8	71.4	-	1.19	0.01	0.95
DOR 108	16.47	0.73	2.69	72.34	-	1.14	-	0.7
DOR 109	15.92	0.75	2.8	72.3	-	1.14	0.02	0.91
DOR 110	16.56	0.81	2.78	68.65	0.15	0.21	0.85	1.02
DOR 111	14.73	1.11	3.07	65.81	0.22	0.19	0.64	1.08
DOR 112	16.35	0.82	2.63	69.85	0.15	0.2	0.93	1.02
DOR 113	16.25	0.86	2.7	69.08	0.13	0.27	0.88	0.93
DOR 115	16.57	1.33	2.21	66.95	0.21	0.28	0.81	1.43
DOR 116	16.55	0.84	2.71	67.86	0.13	0.28	0.89	0.75
DOR 117	14.8	0.98	2.77	69.81	0.19	0.21	0.82	1.08
DOR 118	16.19	0.81	2.85	69.74	0.15	0.17	0.86	0.94
DOR 119	15.78	0.81	2.75	68.22	0.14	0.18	0.69	0.85
DOR 120	16.51	0.85	2.6	68	0.17	0.19	0.84	1.11
DOR 121	17.27	0.86	2.63	69.12	0.1	0.24	0.97	0.78
DOR 122	15.13	1.01	2.3	67.69	0.11	0.23	1	1
DOR 123a	16.92	0.84	2.91	67.41	0.09	0.22	1	0.61
DOR 123b	17.28	0.85	2.69	68.44	0.08	0.21	0.97	0.69
DOR 124	15.07	0.71	2.98	68.85	0.22	0.15	0.72	0.86
DOR 125	17.6	0.77	2.38	71.25	0.09	0.2	1.09	0.49
DOR 126	16.11	0.7	2.48	70.13	0.08	0.24	1.15	0.57
DOR 127	17.21	0.7	2.67	69.84	0.05	0.16	0.99	0.62
DOR 128	17.17	0.69	2.51	70.15	0.08	0.17	1.1	0.6
DOR 129	16.51	0.87	2.83	66.66	0.15	0.17	0.86	0.97
DOR 130a	14.07	0.94	2.81	69.25	0.19	0.19	0.72	0.93
DOR 130b	16.2	0.81	3.44	69.36	0.19	0.19	0.49	1
DOR 131	16.97	0.72	2.77	69.13	0.11	0.19	0.72	0.62
DOR 132	16.29	0.87	2.94	67.68	0.24	0.17	0.71	1.31
DOR 133	15.4	0.74	2.8	68.69	0.19	0.24	0.69	0.98
DOR 134	15.33	0.81	2.63	68.6	0.1	0.23	1.04	0.69
DOR 135	16.54	1.02	2.94	69.59	0.25	0.2	0.35	1.14
DOR 136	1.21	8.09	1.07	63.76	2.06	0.08	0.03	7.51
DOR 137	15.96	0.8	2.74	68.3	0.19	0.21	0.78	0.95
DOR 138	14.71	0.86	2.91	69.39	0.25	0.19	0.78	0.87
DOR 139	15.84	0.72	2.82	69.19	0.16	0.17	0.78	1.02
DOR 141	15.74	0.87	2.8	68.08	0.22	0.19	0.81	1.1
DOR 142	15.95	0.85	2.77	68.54	0.15	0.21	0.66	0.85
DOR 143	17.47	0.9	2.7	67.55	0.1	0.28	1.06	0.54

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
7	0.12	-	0.67	0.01	0.29	-	0.02	0.27	101.9
7.29	0.16	-	0.72	-	0.28	0.01	0.15	-	99.54
6.8	0.14	-	2.14	0.01	0.2	-	1.11	0.38	99.53
6.93	0.12	-	0.84	0.03	0.12	0	0.09	0.63	102.22
6.81	0.14	0.02	0.84	-	0.39	-	0.2	0.77	102.34
6.97	0.14	-	0.66	0.02	0.27	-	0.06	1.09	103.28
7.16	0.12	-	0.8	0.02	0.22	0.01	0.05	-	102.22
7.25	0.11	0.56	0.83	0	0.25	-	0.06	0.41	100.48
7.03	0.2	0.63	1.86	0.02	0.08	0.25	0.55	3.31	100.79
7.27	0.15	0.57	0.74	0.01	0.21	-	0.16	0.35	101.41
7.29	0.16	0.77	0.79	-	0.35	-	0.08	0.39	100.91
7.89	0.15	1.18	0.98	0.01	0.19	-	0.1	0.14	100.43
7.6	0.17	1	0.78	0.01	0.22	-	0.21	0.38	100.39
7.6	0.18	0.77	0.86	0.02	0.34	-	0.08	0.35	100.87
7.18	0.09	0.73	0.72	-	0.26	-	-	0.33	101.01
7.12	0.1	0.53	0.72	0.01	0.3	-	0.29	0.63	99.11
7.78	0.14	0.71	0.75	-	0.27	-	0.06	0.31	100.28
6.96	0.15	0.89	0.73	0.02	0.25	-	0.1	0.29	101.37
9.49	0.25	1.27	0.82	-	0.11	-	-	0.09	100.5
7.27	0.2	1.16	0.84	0.04	0.2	-	0.1	0.11	99.9
7.65	0.15	1.08	0.85	-	0.22	-	-	0.02	101.18
6.78	0.18	0.42	2.49	0.02	0.34	-	0.03	0.9	100.7
6.22	0.13	0.49	0.5	-	0.41	-	-	0.08	101.7
6.21	0.13	0.57	0.55	0.02	0.59	-	0.07	0.16	99.76
7.02	0.11	0.87	0.42	0.01	0.3	-	0.02	-	100.99
6.81	0.09	0.67	0.5	-	0.35	-	-	-	100.89
6.9	0.1	0.61	0.82	0.02	0.42	-	0.34	1.16	99.37
6.95	0.11	0.63	0.82	0	0.37	-	0.27	0.29	98.55
6.56	0.2	0.51	1.14	0.04	1.07	-	-	0.37	101.57
6.58	0.15	0.38	0.74	0.01	0.63	-	0.03	0.19	99.95
7.97	0.15	0.58	0.89	0.01	0.23	0.03	0.25	0.46	100.77
7.11	0.1	0.58	0.74	-	0.39	0.12	0.34	1.03	100.13
6.92	0.13	0.63	0.98	-	0.68	-	0.53	1.36	100.66
7.74	0.13	0.77	0.73	-	0.17	-	-	0.03	101.6
13.21	0.07	0.93	0.52	-	0.33	-	-	0.09	98.95
7.17	0.14	0.65	0.78	0.03	0.44	-	0.08	0.43	99.63
7.26	0.15	0.63	0.85	0.02	0.33	-	0.12	0.85	100.15
7.4	0.12	0.43	0.91	0.02	0.27	0.21	0.01	0.12	100.18
7.37	0.15	0.66	0.85	0.03	0.41	0.05	0.19	1.05	100.56
7.1	0.15	0.51	0.88	-	0.74	-	0.33	1.07	100.76
7.13	0.16	0.7	1.09	0.03	0.74	-	0.29	0.09	100.83

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P2O$_5$	SO_3	Cl	K2O
DOR 144	15.19	0.56	2.33	71.88	0.08	0.2	1.11	0.5
DOR 145	14.25	0.65	2.56	69.38	0.08	0.29	0.88	0.61
DOR 146	16.97	0.42	2.02	67.79	0.05	0.36	1.38	0.4
DOR 147	15.32	0.68	2.62	66.99	0.09	0.31	0.73	0.57
DOR 148	11.36	0.54	2.54	62.79	0.19	0.18	0.8	0.62
DOR 149	10.79	0.44	1.99	41.2	0.05	0.1	0.49	0.47
DOR 149 mineral	1.52	0.03	0.81	9.1	-	-	0.14	-
DOR 150	1.49	1.87	7.54	43.81	1.29	0.02	0.02	3.66
DOR 151	1.2	1.82	6.38	43.41	1.12	0.01	0.01	3.7
Deventer glass samples								
DEV 1	3.1	1.1	7.81	64.21	0.25	0.1	0.11	9.97
DEV 2	16.95	0.73	2.56	69.18	0.06	0.34	0.92	0.53
DEV 3	16.19	0.72	2.81	70.23	0.16	0.25	0.96	0.92
DEV 4	7.2	1.91	1.38	63.86	0.15	0.16	0.38	13.77
DEV 5	10.25	1.81	1.26	64.4	0.47	0.13	0.5	10.44
DEV 6	2.83	5.98	2.99	59.23	2.28	0.05	0.55	12.68
DEV 7	3.25	6.04	3.48	59.99	2.29	0.14	0.58	11.47
DEV 8	0.4	4.16	0.95	60.66	2.07	0.08	0.08	11.62
DEV 9	12.87	1.56	1.93	73.24	0.04	0.06	0.03	0.58
DEV 10	14.55	0.97	2.84	69.44	0.24	0.12	0.9	1.57
DEV 11	14.97	0.69	2.89	70.25	0.18	0.14	0.94	0.61
DEV 12	16.06	0.84	2.74	69.76	0.12	0.21	0.89	0.9
DEV 13	16.76	0.95	2.23	70.38	0.04	0.19	1.19	1.39
DEV 14	0.99	4.39	2.05	59.15	2.97	0.15	0.37	11.85
DEV 15	1.11	3.91	3.29	53.43	4.38	0.53	0.18	17.01
DEV 16 weathered	0.55	0.15	5.85	75.71	-	0.13	0.03	5.38
DEV 17 weathered	0.05	0.03	1.47	82.61	-	0.01	0.04	1.46
DEV 18	8.27	3.48	2.17	60.23	2.47	0.15	0.46	9.17
DEV 19	16.8	0.94	2.76	69.01	0.12	0.21	0.85	1.1
DEV 20	15.98	1.03	2.5	71.68	0.08	0.22	1.22	0.75
DEV 21	0.54	3.54	2.6	59.36	1.87	0.06	0.04	9.52
DEV 22	7.84	1.91	1.24	63.73	0.18	0.19	0.38	14.54
DEV 23 weathered	2.7	0.88	1.08	78.46	1.22	0.13	0.05	2.97
DEV 24	2.92	3.82	1.61	56.1	3.89	0.15	0.39	4.1
DEV 25	13.63	1.84	1.22	69.37	0.17	0.19	0.43	8.03
DEV 26	1.47	3.59	1.24	55.88	2.76	0.16	0.15	17.79
DEV 27	1.84	5.2	3.19	54.63	3.64	0.17	0.17	13.09
DEV 28	3.29	6.25	2.99	58.73	2.35	0.03	0.49	12.73
DEV 29	0.4	3.78	2.24	56.24	2.18	0.1	0.02	10.59
DEV 30a	1.26	3.75	2.82	50.15	1.92	0.21	0.26	18.18
DEV 30b	0.28	0.64	6.05	86.49	-	0.03	0.08	1.57

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
5.96	0.09	0.59	0.76	0.15	1.16	-	0.2	-	100.76
6.55	0.12	0.37	0.75	0.02	2.61	-	0.09	0.62	99.83
5.77	0.06	0.02	0.43	0.01	2.89	-	2.5	0.14	101.2
6.9	0.1	0.55	0.54	-	1.98	-	0.94	1	99.31
6.91	0.11	0.97	0.5	-	0.59	-	1.79	10.66	100.56
3.78	0.14	0.31	0.49	0.01	-	3.01	0.29	39.12	102.66
0.99	0.04	0.08	0.36	-	-	26.72	0.26	62.64	102.68
12.28	0.22	0.18	2.3	0	0.66	-	-	21.95	97.29
13.75	0.24	0.22	2.27	0.02	0.69	-	-	22.12	96.95
10.95	0.47	0.03	2.29	0.02	0.54	-	-	-	100.95
6.95	0.1	0.87	0.96	0.06	0.05	-	-	0.11	100.38
6.75	0.17	0.59	0.66	0	0.32	-	0.08	0.18	100.99
5.77	0.11	1.08	0.49	0.01	0.77	-	0.11	2.83	99.98
8.6	0.07	1.24	0.47	0	0.54	-	-	0.08	100.24
11.09	0.24	0.75	0.76	-	0.54	-	0.06	0.01	100.03
10.59	0.29	0.65	0.9	-	0.59	-	0.2	-	100.45
17.98	0.11	0.72	0.31	0.02	0.56	-	-	-	99.72
10.43	0.03	0.01	0.31	-	0.05	-	0.04	0.03	101.2
8.46	0.21	0.48	0.94	0.01	0.13	-	0.13	0.05	101.04
9.02	0.25	0.17	0.88	-	0.05	-	0.17	0.01	101.22
6.73	0.16	0.91	0.73	-	0.24	-	0.01	0.07	100.37
6.51	0.09	1.09	0.98	-	0.02	-	0.01	0.01	101.83
15.24	0.29	0.72	1	-	0.54	-	0.12	-	99.82
13.73	0.2	0.38	0.93	0.02	0.79	-	0.15	0.03	100.06
1.93	0.24	0.04	0.44	-	0.19	-	-	0.06	90.7
0.81	0.15	0.01	0.12	0.02	0.2	-	0.01	-	86.99
11.5	0.17	0.64	0.96	0.02	0.5	-	0.07	0.09	100.33
7.06	0.16	1.09	0.99	0.01	0.19	-	-	0.21	101.48
6.08	0.08	1.08	1.02	0.02	0.04	-	0.05	0.02	101.84
17.78	0.36	0.87	0.85	0	0.61	-	-	-	98
5.13	0.08	0.49	0.23	-	0.74	-	-	2.42	99.09
1.33	0.11	0.28	0.36	0.02	0.12	-	0.1	0.09	89.9
23.59	0.14	1.23	0.55	0.04	0.26	-	-	0.01	98.79
4.36	0.12	0.49	0.26	0.01	0.37	-	-	0.01	100.49
11.95	0.07	0.42	0.42	-	0.86	-	2.46	0.06	99.28
14.31	0.3	0.79	1.25	-	0.54	-	0.23	-	99.35
10.79	0.18	0.72	0.84	0.02	0.62	-	0.02	0.13	100.18
21.15	0.27	0.74	0.71	-	0.54	-	-	-	98.97
17.56	0.12	0.95	0.61	0.02	0.93	-	-	-	98.72
0.99	0.1	0.01	0.26	0.13	0.06	-	0.05	0.07	96.8

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
DEV 31	14.97	0.59	2.6	70.13	0.15	0.1	1.11	0.71
DEV 32	0.89	5.4	0.74	54.94	2.77	0.21	0.11	12.71
DEV 33	0.84	4.78	0.88	57.22	2.08	0.06	0.54	17.03
DEV 34 weathered	-	-	-	-	-	-	-	-
DEV 35	2.09	5.14	0.98	52.27	3.08	0.19	0.23	13.77
DEV 36	1.18	3.72	1.24	56.07	3.15	0.2	0.13	17.51
DEV 37	18.06	1.8	1.91	63.98	0.53	0.04	1.25	4.77
DEV 38	1.38	3.52	1.02	58.08	3.2	0.23	0.27	16.1
DEV 39	0.74	4.46	2.41	56.75	3.12	0.04	0.27	14.09
DEV 40a	14.95	0.62	2.61	67.97	0.12	0.16	0.87	0.82
DEV 40b	14.93	0.67	2.7	70.23	0.14	0.13	0.91	0.71
DEV 41	14.55	1.08	2.62	67.19	0.41	0.2	0.92	1.97
Susteren glass samples								
Sust 1 (bead body)	16.71	0.83	2.76	63.08	0.18	0.1	0.82	0.83
Sust 2 (bead body)	18.01	0.81	2.75	68.22	0.08	0.18	0.88	0.84
Sust 2 (decoration)	16.31	0.74	2.61	62.49	0.2	0.19	0.81	0.95
Sust 3 (bead body)	15.85	3.4	2.79	65.12	0.25	0.27	0.53	1.9
Sust 3 (decoration)	8.98	0.39	1.5	36.15	0.08	0.03	0.44	0.51
Sust 4 (bead body)	16.88	5.75	2.06	64.47	0.23	0.18	0.68	1.86
Sust 4 (decoration)	16.81	1.36	2.72	67.7	0.15	0.15	0.85	1.57
Sust 5 (bead body)	20.03	0.78	2.49	66.7	0.1	0.23	1.17	0.68
Sust 5 (decoration)	18.5	0.65	2.52	67.29	0.1	0.6	1.15	0.7
Sust 6 (bead body)	16.96	0.75	3.05	69.97	0.06	0.16	0.92	1.21
Sust 6 (decoration)	17.67	0.85	2.79	67.06	0.13	0.22	0.91	1
Sust 7	18.89	0.71	2.47	67.15	0.08	0.32	1.05	0.64
Sust 8	18.99	0.78	2.44	66.01	0.09	0.37	1.08	0.58
Sust 9	17.24	0.84	2.95	64.99	0.1	0.16	0.62	0.78
Sust 10	19.29	0.83	2.6	65.33	0.09	0.29	0.84	0.66
Sust 11	1.9	5.6	2.46	59.06	2.53	0.06	0.47	14.21
Sust 12	17.99	0.99	2.72	66.44	0.21	0.22	0.98	0.84
Sust 13	16.98	1.98	2.66	64.89	0.21	0.22	0.8	1.48
Sust 14	16.18	1.17	2.64	65.83	0.31	0.19	0.82	1.27
Sust 15	18.29	1.07	2.66	62.45	0.15	0.28	1.23	0.74
Sust 16	15.07	1.41	3.6	66.99	0.31	0.16	0.74	1.54
Sust 17	14.26	0.66	2.33	65.14	0.18	0.24	0.67	5.2
Sust 18	13.96	0.88	7.74	63.34	0.31	0.04	0.03	3.3
Sust 19	8.87	3.69	2.23	61.74	1.5	0.16	0.47	8.5
Sust 20	19.04	0.86	2.58	64.85	0.1	0.35	1.26	0.64
Sust 21	16.48	1.05	2.68	67.22	0.19	0.18	0.83	1.1
Sust 22	16.56	1.08	2.69	67.45	0.27	0.27	0.81	1.24
Sust 23	18.06	1.01	2.6	66.25	0.37	0.22	0.96	0.84

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
9.33	0.3	0.12	0.86	0.02	-	-	0.19	0.07	101.25
20.26	0.09	0.53	0.31	0.01	0.64	-	0.07	-	99.68
14.37	0.1	0.57	0.41	-	0.71	-	-	-	99.58
-	-	-	-	-	-	-	-	-	0
17.69	0.11	2.36	0.44	0.01	0.5	-	-	0.09	98.94
14.31	0.11	0.39	0.44	0	0.72	-	0.1	-	99.27
7.55	0.12	0.08	0.46	0.01	0.21	-	-	-	100.77
14.59	0.05	0.35	0.31	-	0.66	-	0.06	-	99.81
15.19	0.26	0.4	0.83	-	0.61	-	0.08	0.03	99.28
8.89	0.23	0.18	0.88	0	0.06	-	2.29	0.13	100.78
8.95	0.27	0.17	0.88	0.02	0.07	-	0.09	0.29	101.14
7.01	0.11	0.53	0.56	-	0.24	-	2.57	0.02	99.97
7.08	0.17	0.63	5.09	0.01	0.27	0.23	0.26	1.35	100.4
7.1	0.12	0.62	0.86	0	0.29	0.12	0.27	0.71	101.86
6.74	0.13	0.57	4.59	0.01	0.34	0.28	1.74	1.69	100.38
7.03	0.18	0.54	1.29	0.1	0.2	0.32	0.14	0.24	100.14
3.5	0.12	0.43	0.54	0	0	2.72	0.13	44.29	99.8
7.28	0.1	0.61	0.63	0	0	0	0.12	0.12	100.95
7.68	0.12	0.67	0.95	0.01	0.25	0.14	0.16	0.44	101.73
6.66	0.22	0.84	0.63	0.02	0.34	0	0.03	0.09	101.01
6.28	0.09	0.44	0.69	0	1.79	0	0.16	0.68	101.62
7.15	0.13	0.25	0.38	0	0	0.19	0.39	0.21	100.96
7.97	0.13	0.71	0.82	0.01	0.32	0	0.17	0.22	101.76
6.56	0.11	0.32	0.88	0.07	1.58	0	0.3	0.22	101.35
6.55	0.08	0.37	0.94	0	1.7	0	0.27	0.3	100.53
6.28	0.18	0.54	1.38	0.02	0.48	0.22	3.06	1.3	101.12
7.07	0.13	0.75	0.44	0	0.35	0	0	0.2	98.89
11.02	0.34	0.59	1.01	0	0	0	0.04	0	99.28
7.13	0.2	0.81	0.91	0	0.36	0.14	0.31	0.84	101.09
7.39	0.15	0.55	0.89	0	0.3	0.14	0.28	0.57	99.48
8.89	0.24	0.66	1.05	0.03	0.16	0	0.26	0.36	100.05
6.46	0.18	0.31	1	0	0.69	0.2	0.6	2.73	99.01
7.49	0.2	0.51	1.31	0	0.17	0	0.17	0.58	100.25
7.08	0.1	0.43	1.04	0.07	1.5	0.08	0.25	0.68	99.91
5.81	1.07	0.47	1.35	0.02	0.17	0.06	0.79	0.05	99.37
9.73	0.16	0.7	0.89	0.01	0.25	0.09	0.26	0.46	99.69
6.94	0.11	0.87	0.92	0.01	0.33	0	0.29	0.65	99.79
8.39	0.16	0.6	1.1	0.01	0.18	0	0.2	0.42	100.8
8.28	0.23	0.71	1.01	0.02	0.09	0.13	0.35	0.71	101.89
7.46	0.1	0.43	0.9	0	0.38	0.13	0.28	0.75	100.74

Appendix II major and minor chemical compositions of samples analysed by electron probe microanalysis

Element oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
Sust 24	17.92	0.9	2.8	66.41	0.22	0.24	0.89	0.85
Sust 25	16.61	0.76	2.62	67.02	0.08	0.28	0.82	0.62
Sust 26	19.09	1.16	2.87	65.79	0.08	0.24	1.03	0.68
Sust 27	16.62	1.2	2.61	66.22	0.28	0.17	0.84	1.23
Sust 28	15.38	4.2	2.03	64.61	0.27	0.15	0.66	2.48
Sust 29	17.79	0.84	2.73	66.47	0.15	0.26	0.92	0.76
Utrecht glass samples								
Utr 77	16.45	0.92	2.65	68.09	0.18	0.35	1.1	0.39
Utr 78 modern	-	-	-	-	-	-	-	-
Utr 79	13.5	0.41	1.7	69.87	0.03	0.21	0.03	0.39
Utrecht crucibles								
Utr 31	8.77	0.57	12.6	66.05	0.03	0.01	0.1	4.73
Utr 32	15.54	1.66	4.65	67.07	0.06	-	0.3	1.9
Utr 33	0.37	0.44	36.89	54.29	-	0.04	0.04	2.26
Utr 34	14.39	1.02	2.82	63.59	0.56	0.15	0.2	1.45
Utr 35	13.08	0.76	7.41	69.7	-	0.05	0.24	2.24
Utr 36	8.21	0.84	7.68	66.9	-	0.16	0.07	5.4

CaO	TiO_2	MnO	FeO	CoO	Sb_2O_5	SnO_2	CuO	PbO	Total
7.5	0.18	0.61	0.88	0.03	1.97	0	0.24	0.61	102.25
7.28	0.09	0.34	0.86	0.09	0.24	0	0.24	0.85	98.79
6.27	0.4	1.79	1.26	0.01	0	0	0	0.08	100.74
7.88	0.16	0.65	0.88	0	0.25	0	0.24	0.59	99.82
7.1	0.16	0.6	0.7	0.03	0.11	0	0.06	1.64	100.16
7.24	0.18	0.74	0.95	0	0.5	0.14	0.53	1.4	101.6
6.29	0.11	0.08	0.74	-	-	-	0.06	0.57	97.98
-	-	-	-	-	-	-	-	-	-
10.39	0.03	0.03	0.12	0.08	0.04	-	0.06	0.07	96.97
2.48	0.64	0.14	3.17	0.11	0.45	0.02	0.03	0.09	99.98
5.78	0.21	0.22	1.53	0.14	0.11	0.02	0.01	-	99.19
0.34	2.22	0.02	2.88	0	0.12	0.02	0.01	0	99.93
6.82	0.15	0.73	1.52	0.13	0	-	0.62	4.91	99.07
4.87	0.59	0.37	1.36	0.06	0.29	0.03	1.12	-	102.16
3.29	0.45	0.3	1.59	0.03	0.5	-	0.39	-	95.81

Appendix III trace element chemical compositions of samples analysed by LA-ICP-MS

Trace elements	Li	B	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb
Gennep glass samples																	
GE41	7.4	187.9	27	22	54	27.9	5177.3	258.9	59.5	9.1	484	7.5	88.8	3.3	2.4	2546	4570
GE42	8	351.5	78	133	22.1	27.6	1194.5	31.6	19.4	7.3	522	12.2	181	4.5	2.4	308	1081
GE43	5.1	107	74	40	11.5	22	114.6	32.6	11	6.1	500	10.1	142.7	3.8	3.7	10	24
GE44	6.5	199.3	74	40	12	25.5	231.8	37.5	11.7	6.8	501	10.6	139.1	3.8	3.6	125	163
GE45	7.2	151.3	76	47	16	25.3	358.6	44.7	15.8	7.4	552	11.5	185.5	4.6	3.1	67	175
GE46	4.9	114.7	75	40	11.9	21.9	120.6	37.2	10.8	6	504	10.9	151.8	3.9	3.7	25	68
GE47	7.2	201.3	26	19	37.1	18.2	3408.8	105.9	44.5	8.9	536	7.6	86.1	2.8	2.5	2639	3559
GE48	9.3	158.1	16	12	6.7	7.7	131.3	37.2	10.6	9.2	450	6.5	52.7	1.8	1.3	72	1741
GE49	11.2	165.5	25	18	14.4	11.7	474.3	69.3	10.1	10.7	542	7.5	81	2.6	2.1	608	1021
GE51	10.9	156.4	26	18	14.8	12.3	724.9	69.3	10.7	9.2	575	7.3	82.3	2.8	2.2	571	872
GE52	13.5	187	26	21	58.9	30.5	6044.5	293.6	64.9	11.9	508	8.4	93.3	3.6	2.6	1640	4274
GE53	17.7	142.2	33	17	13.9	13.6	382.5	49.5	6.1	8.8	697	7.7	83.6	2.7	3.6	220	322
GE54	9	208.2	31	18	7.7	16.7	66.5	35.5	5	8.2	734	8.5	99.5	3.2	3.2	445	331
GE55	7.3	203.2	32	17	7.2	11.6	66.9	24.4	4.7	7.5	746	8.4	95.9	3.2	3.6	25	300
GE56	5.7	236.4	34	30	8.7	14.2	34.9	27.8	2.5	5.6	562	8.3	141.4	3.7	4.6	4	1
GE57	11	183.6	32	22	7.5	11	83	25.2	5.2	9.5	693	8.3	89.4	3	2.6	456	267
GE58	11	177.2	31	17	7.8	11.3	85.3	37.8	5.4	10.1	686	8.3	91.2	3.2	2.3	395	340
GE59	9.2	194.8	27	15	6.6	16	217.4	121.2	22.1	22.9	773	8.2	89.4	2.8	3.2	24611	237
GE60	8.1	208.7	33	17	7	12.2	73.4	21.7	4.6	7.4	770	8.4	97	3.3	3.2	9	314
GE61	12.2	174.8	19	14	7.4	9.4	135.8	32.7	11.9	11.3	503	6.9	62.6	2.2	1.5	203	1998
GE62	15.1	165.8	25	18	12.7	11.8	397	76.7	11.2	10.4	545	7.6	77.9	2.6	2.4	704	1469
GE63	11.6	158.2	23	18	8.7	10.5	209.7	40.9	8.1	11	522	7.9	83.2	2.6	2.3	300	1123
GE64	16.4	180.7	26	17	11.7	12.4	242	104.4	9.2	14.2	577	7.8	77.6	2.7	2.3	1315	1148
GE65	12.4	163.3	27	18	17.1	12.3	1042.8	64	13.2	9.1	530	7.6	82.7	2.6	2.7	337	1474
GE66	8.8	159.8	19	14	9	10	337.9	39.1	10.4	8.8	488	6.9	56.8	2	2.7	76	1007
GE67	10.6	169	27	20	14.1	12	456.6	64.3	9.7	8.8	490	7.5	83.2	2.6	3	150	1042
GE68	8.4	170.2	20	14	10.1	10.3	217	43.1	6.4	10.4	506	7.3	59.9	2.1	1.7	254	845
GE69	7.3	173.9	39	46	12	15.2	83.6	33.7	4.6	6	514	9.6	199.7	4.9	5.2	34	8
Maastricht-Jodenstraat (MAJO) glass samples																	
Joden 1	4.5	179.3	26.38	27.36	9.4	41.4	15637.3	4231.5	51.3	18.1	479	10.2	113.3	3.6	3.7	11459	118
Joden 2	7.4	145.9	27.23	15.95	10.9	37.7	15536.7	2119.5	43.5	10.6	615	7.3	81.4	2.8	4.7	6426	206
Joden 3	9	169.1	31.11	16.8	8.4	16.7	90.1	36.6	5.6	9.1	745	7.8	85.2	3.1	4.3	18692	165
Joden 4	8	155.1	50.54	18.22	11.7	22.6	91.6	36	9.9	8.2	649	9.4	97.4	3	3.5	52964	38
Joden 5	6.7	164	30.69	15.05	9.9	23.1	201.4	45.2	11.7	9	631	7	77.9	2.9	5.3	53150	84
Joden 6	11.6	138.8	32.97	19.4	8.7	22.1	302.2	74.7	30.1	17	714	8.9	91.3	3.5	4.2	78067	216
Joden 37	4.5	161.2	13.79	14.41	259.2	82.9	357	23	12.2	14.4	436	6.3	78.5	2.2	3.3	9097	3
Joden 38	4.9	189.7	15.62	12.67	204.7	69.3	823.9	17.6	9.1	6.6	541	6.2	73.8	2.2	2.6	81	6
Joden 39	4.4	163.1	15.09	14.03	311.2	89.9	1070.8	18	9	7.1	491	6.7	78.3	2.2	3.7	33	4
Joden 40	4.3	174.5	14.93	14.02	308.6	97	1059.1	19.3	12.7	7.4	491	6.2	76.3	2.1	4.1	55	4
Joden 41	8.4	166.3	21.8	16.27	35.4	48.2	20139.9	1286.1	65.9	12.5	521	7.9	66.8	2.3	1.7	2182	1513
Joden 42	9.3	153.8	20.55	12.56	32.4	47.9	20130.9	1804.3	72.1	12.9	486	7.7	63.1	2.2	1.9	2413	1648
Joden 43	9.9	158.2	30.69	15.57	13.9	74.5	31204.5	3655.4	53.3	10.4	691	7.8	84.4	3	4.9	8394	252
Joden 44	4.6	121.5	21.88	9.93	4.3	14.7	38.8	18.5	2.1	5.4	572	5	54.8	2	4.4	6	34
Joden 45	15.2	153.9	28.82	18.13	10.7	16.7	152.4	53.1	7.4	10.6	568	7.8	83.1	2.7	3.2	190	684
Joden 46	15.4	157.4	36.32	36.73	9.3	12.6	138.6	57.1	5.5	6.8	470	8.6	157.3	4	3.1	24	357
Joden 47	11.3	166	37.74	17.88	10.8	25.8	277.7	68.8	13.8	12.3	740	9.2	98.3	3.5	4.9	50418	247
Joden 48	10.1	170.8	33.58	16.66	8.9	18.8	1287.7	44.4	3.9	10.5	755	7.6	92.2	3.1	5.3	215	189
Joden 49	9.2	404.3	52.39	28.12	7.6	268.3	5825	2077.4	2.4	41.7	164	20.2	286.3	8.4	0.3	195	66

Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
0.27	327	7.7	13.4	1.7	6.9	1.5	0.4	1.2	0.2	1.2	0.3	0.7	0.1	0.7	0.1	2	0.2	25821	1.3	1.2
0.13	353	11.9	15	2.6	10.8	2.2	0.6	2.4	0.4	2.2	0.4	1.1	0.2	1.3	0.1	4.2	0.3	3265	1.8	1.5
0.09	385	9.9	14.3	2.3	9.9	2	0.5	1.8	0.3	1.8	0.4	1.1	0.2	1.1	0.1	3.4	0.2	125	1.5	1.3
0.08	386	10.7	14.8	2.4	10	2.2	0.6	1.8	0.3	1.7	0.4	1.1	0.1	1	0.2	3.4	0.2	647	1.5	1.3
0.08	464	10.9	16.2	2.6	11.4	2.5	0.6	2.4	0.3	2	0.4	1.1	0.2	1.3	0.2	4.3	0.3	922	1.8	1.4
0.08	396	10.1	14.7	2.4	9.7	1.9	0.6	2	0.3	1.8	0.4	1.1	0.2	1.1	0.2	3.6	0.2	192	1.6	1.3
0.2	321	7.8	13.7	1.8	7.4	1.6	0.4	1.3	0.2	1.3	0.2	0.8	0.1	0.6	0.1	2.2	0.2	18040	1.3	1.3
0.18	262	6.5	11	1.5	5.7	1.3	0.4	1.2	0.2	1	0.2	0.6	0.1	0.5	0.1	1.3	0.1	441	1.1	1
0.21	352	7.3	13.4	1.7	7	1.4	0.4	1.3	0.2	1.2	0.3	0.8	0.1	0.7	0.1	2.1	0.2	2036	1.3	1.2
0.18	360	7.1	13.4	1.7	7.3	1.4	0.4	1.3	0.2	1.2	0.2	0.8	0.1	0.6	0.1	2.1	0.2	3371	1.3	1.2
0.34	367	8.7	14.5	1.9	7.8	1.7	0.4	1.5	0.2	1.3	0.3	0.8	0.1	0.9	0.1	2.3	0.2	16358	1.6	1.2
0.12	439	7.4	12.9	1.8	7.2	1.5	0.3	1.5	0.2	1.4	0.3	0.8	0.1	0.7	0.1	2	0.2	1407	1.3	1.4
0.14	359	8.2	14.7	1.9	7.6	1.8	0.4	1.6	0.2	1.5	0.3	0.9	0.1	0.8	0.1	2.6	0.2	140	1.7	1.4
0.13	361	8.1	14	1.9	7.9	1.6	0.4	1.6	0.2	1.4	0.3	0.8	0.1	0.8	0.1	2.5	0.2	121	1.5	1.6
0.07	415	7.9	14.5	1.9	7.4	1.4	0.4	1.5	0.2	1.4	0.3	0.8	0.1	0.9	0.1	3.4	0.2	16	1.6	1.4
0.17	339	8.4	14.3	2	7.7	1.8	0.4	1.5	0.2	1.5	0.2	0.9	0.1	0.7	0.1	2.2	0.1	262	1.4	1.4
0.18	330	8.3	14.6	2	7.6	1.6	0.5	1.5	0.2	1.5	0.3	0.9	0.1	0.7	0.1	2.3	0.2	356	1.5	1.4
0.22	383	7.7	13.5	1.8	7.7	1.6	0.4	1.7	0.2	1.4	0.3	0.8	0.1	0.7	0.1	2.2	0.2	25043	1.3	1.4
0.11	368	8.3	14.7	1.9	8.3	1.7	0.4	1.9	0.2	1.4	0.3	0.8	0.1	0.9	0.1	2.3	0.2	113	1.5	1.6
0.19	276	6.6	12.4	1.5	6.4	1.3	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.5	0.1	498	1.2	1.1
0.24	367	7.6	13.7	1.7	7.2	1.5	0.4	1.4	0.2	1.3	0.3	0.7	0.1	0.6	0.1	1.9	0.2	1581	1.3	1.1
0.18	342	7.4	12.8	1.7	7.2	1.5	0.4	1.4	0.2	1.3	0.2	0.7	0.1	0.7	0.1	2.1	0.2	713	1.3	1.1
0.27	367	7.7	13.3	1.8	7.1	1.4	0.4	1.5	0.2	1.3	0.3	0.7	0.1	0.7	0.1	1.8	0.1	1361	1.3	1.2
0.22	425	7.6	12.9	1.7	7.2	1.5	0.4	1.4	0.2	1.2	0.3	0.9	0.1	0.7	0.1	2	0.2	3237	1.3	1.3
0.16	348	6.9	12.3	1.6	6.2	1.4	0.4	1.3	0.2	1.2	0.3	0.7	0.1	0.6	0.1	1.4	0.1	803	1.1	1
0.19	387	7.2	13.1	1.7	6.6	1.4	0.4	1.3	0.2	1.2	0.2	0.7	0.1	0.7	0.1	2.1	0.2	1267	1.2	1.1
0.16	303	6.9	12.6	1.6	6.5	1.3	0.4	1.2	0.2	1.3	0.2	0.7	0.1	0.7	0.1	1.6	0.1	700	1.1	1.1
0.07	453	9.1	16.2	2.2	9.1	1.9	0.5	1.9	0.2	1.7	0.3	1.1	0.1	0.9	0.1	4.8	0.3	211	2	1.5
0.26	386	9.9	16.9	2.3	9.5	1.7	0.4	1.8	0.3	1.6	0.3	1	0.1	0.9	0.1	2.8	0.2	88534	1.9	1
0.26	274	7.5	14	1.8	7	1.5	0.4	1.3	0.2	1.3	0.3	0.8	0.1	0.7	0.1	2.1	0.2	61933	1.4	1.1
0.24	339	8	14.1	1.8	7.8	1.6	0.5	1.5	0.2	1.4	0.3	0.9	0.1	0.8	0.1	1.9	0.2	2319	1.4	1.2
0.31	350	9.3	13.7	2.1	8.4	1.7	0.5	1.8	0.3	1.7	0.3	0.9	0.1	0.9	0.1	2.3	0.2	47497	1.5	1.1
0.46	268	7.1	12.7	1.6	6.6	1.3	0.4	1.4	0.2	1.2	0.2	0.7	0.1	0.6	0.1	2	0.2	316647	1.3	1.3
1.05	239	9.5	17.5	2.2	8.9	1.8	0.4	1.8	0.3	1.5	0.3	0.9	0.1	0.9	0.1	2.4	0.2	780143	2.2	1.1
0.06	151	6.1	11.1	1.4	5.7	1.2	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	2	0.1	5767	1.1	1.1
0.08	159	5.9	10.8	1.5	5.8	1.3	0.3	1.2	0.2	1	0.2	0.6	0.1	0.6	0.1	1.7	0.2	3529	1	1.2
0.1	155	6.3	11.3	1.4	5.9	1.2	0.3	1.1	0.2	1.2	0.2	0.7	0.1	0.7	0.1	2.1	0.1	5276	1.1	1
0.07	155	6.3	11.3	1.4	6.3	1.2	0.4	1	0.2	1	0.3	0.8	0.1	0.6	0.1	1.9	0.1	5394	1.1	1
0.39	298	7.8	13.1	1.7	6.9	1.4	0.5	1.3	0.2	1.3	0.2	0.9	0.1	0.6	0.1	1.5	0.2	75113	1.3	1
0.54	270	7.3	13.1	1.7	7.3	1.4	0.4	1.3	0.2	1.3	0.3	0.8	0.1	0.8	0.1	1.6	0.1	84741	1.4	1.2
0.22	297	7.8	14.2	1.8	7.8	1.7	0.4	1.6	0.2	1.2	0.3	0.8	0.1	0.8	0.1	2.2	0.2	7289	1.3	1.1
0.08	217	5	9.1	1.2	4.7	1	0.2	1	0.1	0.9	0.2	0.6	0.1	0.4	0.1	1.4	0.1	40	0.9	0.8
0.24	346	7.5	13.2	1.8	7.3	1.8	0.4	1.4	0.2	1.3	0.2	0.7	0.1	0.7	0.1	2.1	0.2	338	1.3	1.1
0.08	1529	8.1	14.4	2	7.2	1.4	0.6	1.5	0.2	1.6	0.3	1	0.1	1	0.1	3.9	0.3	178	1.6	1.2
0.55	314	9.6	15.6	2.2	9.1	1.8	0.4	1.9	0.3	1.6	0.3	0.9	0.1	0.9	0.1	2.4	0.2	407431	1.7	1.2
0.18	343	8	14.2	2	7.7	1.6	0.4	1.6	0.2	1.3	0.2	0.8	0.1	0.7	0.1	2.3	0.2	835	1.5	1.2
1.69	234	19.9	38.5	4.3	16.3	3.6	0.7	3.6	0.5	3.8	0.7	2.5	0.3	1.9	0.4	7.9	0.6	297	5.9	2

Appendix III trace element chemical compositions of samples analysed by LA-ICP-MS

Trace elements	Li	B	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb
Joden 50	5.1	138.1	41.79	18.01	10.6	22.8	94.2	71.2	12.9	72.6	482	7.8	85.6	2.9	9.3	124317	122
Joden 51	6.8	139.1	25.17	13.94	12	38.4	7657.8	1092	29.2	8.4	608	5.8	65.9	2.4	4.6	6446	188
Joden 52	7.2	149.9	28.97	14.81	12.1	75.3	42945.3	5559.9	74.4	8.6	666	6.9	84.1	2.8	5.1	1830	159
Joden 53	4	160.5	17.07	15.45	178.8	47.2	805.3	22.5	7.6	6.7	365	5.9	84.2	2.5	2.5	3897	3
Joden 54	7.9	143.4	34.27	15.11	24.7	42.3	9609.1	1721.7	32.7	10	548	7	70.7	2.7	3.3	11562	170
Joden 55	8.1	88.9	21.38	13.91	9.3	68.3	5565.2	6530.8	85.4	10.9	426	5.5	58.4	2.3	2.7	10115	92
Joden 56	6.6	114.8	23.68	12.84	6.2	15.2	126	35	10	8.6	561	6.1	65.8	2.4	4	30841	169
Joden 57	6	159.1	25.4	14.58	20.7	88.3	26978.6	1474.6	43.2	8.6	602	7.1	74.6	2.7	4.4	5930	110
Joden 58	5.6	165.1	32.57	14.07	9.3	21.5	57.6	38.4	9.7	7.9	660	6.5	70	2.5	5.5	41978	60
Joden 59	7.5	157.7	31.1	14.33	9.5	16.9	112.2	36.8	7.7	9.1	659	7.2	77.2	2.6	4.3	27321	212
Joden 60	0.1	237	0.34	29.13	1.3	14.9	82	68.6	0.9	0.2	7	0.2	0.7	-	-	376	11
Joden 61	12.5	195.2	18.66	11.61	378.8	22.6	2057.6	59.8	43.4	13.1	441	6.4	60.7	2.2	2.1	124	11536
Joden 62	11.1	160.3	32.81	17.08	7.1	16.1	51.1	29	5.1	8.7	788	7.9	100.7	3.2	5.4	10	99
Joden 63	6.3	166.7	30.21	16.38	7.5	16.1	7.3	26.6	3.3	10.8	860	7.5	84.6	2.9	5.6	684	179
Joden 64	5.2	99.1	21.46	12.13	4.6	15.1	121.4	32.3	17.1	8.5	401	5	59.9	2.3	3.3	39547	98
Joden 65	5.6	93.9	18.73	10.93	5.2	10.9	136.2	36.5	7.7	7.1	481	4.7	51.3	1.9	3.3	23702	121
Joden 66	7.3	161	33.09	17.2	14.2	53.5	14623.8	2929.4	46.4	10.4	655	7.2	81.4	3	4.9	14412	113
Joden 67	10.6	150.4	31.43	16.77	13.5	65.5	26901	4409.2	60.3	11.8	648	8.1	84.9	2.8	4.6	1585	215
Joden 68	3.6	133.6	12.57	32.33	15.6	9.5	154.7	18.7	2.1	9.1	389	6.1	45.5	1.5	1.5	34	592
Joden 69	7.2	105.3	43.54	15.87	10.1	23.2	183.8	39.1	11.4	8.5	473	7.8	67.1	2.5	2	104859	109
Joden 70	8.6	137.9	30.49	15.75	8.7	19.7	182.4	52.5	6.7	9.6	631	7.3	78.6	2.8	4	24800	153
Joden 71	6.8	100.4	40.71	12.9	8.7	21.7	238.1	36	11.6	8.9	450	7.2	62.3	2.3	2.4	39902	86
Joden 72	6.2	136	24.71	13.51	8.2	18.2	116.7	37.4	10.6	9.1	496	6.1	65.6	2.4	4.4	37442	70
Joden 73	6.5	154	28.16	15.2	19.3	96.5	28045.7	1778.3	50.9	7.9	737	6.9	86.6	2.7	5.3	18725	183
Joden 74	6	149.3	26.78	15.54	19.3	89.8	27398.5	1726.3	47.4	7.5	717	6.8	80.7	2.7	5	5641	154
Joden 75	8.5	136.6	34.06	14.53	12.2	62.7	28328.3	3250.1	63.5	9.3	582	7.2	70.6	2.4	3.2	50978	294
Joden 76	6	150.4	27.77	14.63	18.9	90.7	26781	1682	46	7.5	719	7.2	80.1	2.6	5.2	5800	154
Wijnaldum glass samples																	
WIJ1	10.1	163.4	28.18	15.89	9.8	11.2	230.1	54.6	7.1	9.6	631	8.6	79.7	2.5	2.1	402	626
WIJ2	19	174.3	27.85	18.31	11.3	11.7	576.3	70.2	8.8	10.4	598	8.3	89.6	2.7	2.3	542	989
WIJ3	15	168.2	28.67	17.59	12.1	12.4	573.4	144.8	9.9	11.5	625	8.9	86.4	3	2	997	803
WIJ4	2	104.8	4.39	4.29	1.2	7.9	224.2	19.2	45	4	215	3.3	24	0.8	0.1	23001	3049
WIJ5	7.6	97.8	32	14.76	9.6	23.1	155.4	42.3	12.6	15.2	363	9.2	59.6	2.4	1	43112	117
WIJ6	6.2	95.2	28.12	17.75	9.6	20.9	214.4	32	23.6	7.7	343	8.2	71.5	3.2	1.1	59853	112
WIJ 7	8.4	93.3	32.74	18.13	18.1	35.6	199.4	83.6	8	13.2	565	7.8	74.4	2.8	4.3	43807	173
WIJ 8	6.8	49.2	12.74	12.58	2.2	12.7	190.3	15.2	2.6	11.1	240	5.2	29.1	1.5	0.4	37252	1
WIJ 9	8	41	10.88	11.2	2.1	13.4	263.5	29.2	4.3	12	212	4.7	25.6	1.6	0.3	46669	1
WIJ 10	9.2	90.9	21.33	26.39	8.7	8.3	375.9	56.6	3.2	8.2	235	7.1	184.7	3.9	0.5	82	156
WIJ 11	55.6	145.4	20.82	17	8.8	10.7	698.3	181.8	14.6	16.3	440	7	75.2	2.5	1.7	221	1802
WIJ 12	8.1	164.2	23.24	21	6.5	9	123	38.3	13.3	9.8	458	7.5	95.5	2.6	2.2	35	1679
WIJ 13	8.8	163.8	22.45	17	6.5	9.1	74.6	29.9	11.3	8.9	485	7.2	73.6	2	2	19	2258
WIJ 14	8	60.9	17.15	17	4.8	29.6	290.8	54.8	18	15.8	136	4.7	57.6	3.4	0.3	63145	53
WIJ 15	4	98.5	20.28	26	822.5	25.1	934.3	2256.1	11.2	4.2	177	6.6	169.1	3.9	2.6	97	7
WIJ 16	6.5	76.7	9.91	9	7.6	6.8	1172.2	42.8	9.7	8.3	283	4.7	38.9	1.2	0.9	359	828
WIJ 17	20.2	76.1	50.3	22	51.6	118.8	19996.3	2905.8	89.5	46.2	287	14	197.5	6.7	3.6	2095	145
WIJ 18	13.1	151.6	52.76	22	25.4	48.4	18941.6	2536.3	65.1	14.4	528	10.9	99.5	3.5	3.4	7748	551

Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
0.8	304	8	12.9	1.9	7.7	1.4	0.4	1.5	0.2	1.3	0.3	0.8	0.1	0.6	0.1	2	0.2	23851	1.3	0.9
0.16	238	6.2	11.2	1.4	5.8	1.1	0.3	1.1	0.2	1	0.2	0.6	0.1	0.6	0.1	1.6	0.2	78875	1.1	1
0.15	280	6.9	12.3	1.6	6	1.6	0.3	1.3	0.2	1.2	0.2	0.7	0.1	0.6	0.1	2	0.1	3115	1.3	1.1
0.08	159	6.4	12	1.6	5.8	1.2	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.7	0.1	2.1	0.2	4798	1.1	1
0.23	276	7.6	12.8	1.7	6.9	1.3	0.4	1.3	0.2	1.2	0.3	0.7	0.1	0.7	0.1	1.7	0.1	71856	1.3	1.1
0.57	259	7.1	11.2	1.4	6	1.2	0.2	0.9	0.2	1	0.2	0.5	0.1	0.6	0.1	1.5	0.1	354763	1.3	1.7
0.39	186	6.3	11.2	1.5	6.6	1.2	0.3	1.1	0.2	1	0.2	0.7	0.1	0.5	0.1	1.6	0.1	277719	1.3	0.9
0.18	275	7.1	12.7	1.7	6.9	1.6	0.4	1.6	0.2	1.2	0.3	0.6	0.1	0.8	0.1	1.8	0.2	37801	1.3	1
0.18	317	6.8	11.4	1.5	6.2	1.3	0.3	1.3	0.2	1.2	0.2	0.8	0.1	0.7	0.1	1.7	0.1	22283	1.1	1.2
0.19	270	6.8	12.4	1.7	6.7	1.3	0.4	1.4	0.2	1.1	0.3	0.7	0.1	0.7	0.1	2	0.2	28303	1.2	1.3
0.11	9	0.3	2.4	0	0.1	0	0	0.1	0	0	0	0	0	0	0	0.1	0	2484	0	0
0.41	261	6.9	11.7	1.5	5.8	1.3	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.5	0.1	2011	1.2	1.1
0.13	293	7.7	14.4	1.8	7.8	1.5	0.5	1.6	0.2	1.3	0.3	0.9	0.1	0.8	0.1	2.4	0.2	88	1.4	1.2
0.1	258	7.3	13.3	1.7	7.1	1.4	0.4	1.5	0.2	1.3	0.3	0.7	0.1	0.7	0.1	2.2	0.2	205	1.3	1.2
0.64	167	5.2	8.8	1.2	4.6	1.1	0.2	0.8	0.1	0.9	0.2	0.5	0.1	0.5	0.1	1.5	0.2	468522	1.1	0.7
0.34	150	4.9	8.9	1.2	4.6	0.9	0.2	0.9	0.1	0.8	0.2	0.5	0.1	0.5	0.1	1.4	0.1	221741	0.9	0.7
0.3	291	7.6	14.2	1.8	7.3	1.5	0.4	1.6	0.2	1.4	0.3	0.7	0.1	0.7	0.1	2.1	0.5	123336	1.5	1.3
0.24	318	7.8	15.2	1.9	7.7	1.7	0.4	1.5	0.2	1.4	0.3	0.8	0.1	0.8	0.1	2.1	0.2	38984	1.5	1.1
0.15	224	5.9	10.6	1.4	5.1	0.9	0.3	1.1	0.2	0.9	0.2	0.6	0.1	0.5	0.1	1.2	0.1	182	1	0.9
0.6	261	7.8	12.3	1.8	7.4	1.4	0.3	1.5	0.2	1.3	0.3	0.8	0.1	0.7	0.1	1.8	0.2	423852	1.3	0.9
0.34	249	7.6	13.4	1.7	7.3	1.5	0.3	1.4	0.2	1.4	0.2	0.7	0.1	0.6	0.1	2	0.2	206637	1.3	0.9
0.43	265	7.1	10.8	1.6	6.3	1.1	0.3	1.5	0.2	1.3	0.3	0.8	0.1	0.6	0.1	1.6	0.1	288546	1.1	0.8
0.44	221	6.5	11.8	1.4	6.1	1.3	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.5	0.1	1.5	0.1	294751	1.2	1.1
0.22	254	7.2	13.3	1.7	6.9	1.5	0.3	1.3	0.2	1.4	0.2	0.7	0.1	0.7	0.1	2.2	0.2	40403	1.3	1.1
0.18	252	7	12.5	1.6	6.5	1.2	0.3	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.9	0.2	38669	1.3	1
0.5	283	7.9	12.9	1.8	7.3	1.5	0.4	1.5	0.2	1.4	0.3	0.7	0.1	0.8	0.1	1.7	0.2	59580	1.3	0.9
0.24	249	7.2	12.7	1.6	6.6	1.4	0.4	1.2	0.2	1.2	0.2	0.7	0.1	0.7	0.1	2	0.2	38566	1.3	1.1
0.14	320	8.1	13.8	1.9	7.6	1.7	0.5	1.6	0.2	1.4	0.3	0.7	0.1	0.9	0.1	2	0.2	1149	1.3	1.2
0.14	399	8.2	13.9	2	7.8	1.5	0.4	1.5	0.2	1.3	0.3	0.8	0.1	0.9	0.1	2.3	0.2	1409	1.4	1.1
0.21	357	8.4	14.8	2	8.3	1.7	0.5	1.4	0.2	1.3	0.2	0.8	0.1	0.8	0.1	2.4	0.2	2525	1.4	1.2
0.1	85	3.1	5.4	0.7	3	0.8	0.2	0.6	0.1	0.5	0.1	0.3	0.1	0.3	0	0.7	0	328951	0.4	0.5
0.83	177	9.6	15.4	2.3	8.7	1.8	0.4	2	0.3	1.6	0.3	1	0.1	0.9	0.1	1.6	0.2	496383	1.7	0.9
0.29	150	7.8	12.2	1.7	7.1	1.5	0.3	1.2	0.2	1.4	0.3	0.9	0.1	0.9	0.1	1.9	0.2	477936	1.6	0.9
0.66	222	8.8	13.4	2.1	8	1.5	0.4	1.6	0.2	1.5	0.3	0.8	0.1	0.8	0.1	1.9	0.2	508491	1.6	1
0.62	156	5.3	10.3	1.2	5.2	1	0.3	0.9	0.1	0.9	0.2	0.5	0.1	0.4	0	0.8	0.1	440657	1.1	1
0.68	139	4.9	9.8	1.2	4.6	1	0.3	0.9	0.1	0.7	0.2	0.5	0.1	0.4	0.1	0.7	0.1	545641	1.2	0.5
0.1	199	7.3	13.9	1.8	7	1.6	0.4	1.3	0.2	1.2	0.2	0.7	0.1	0.7	0.1	4.5	0.3	584	1.6	1.1
0.25	316	7.4	13	1.6	7	1.3	0.3	1.3	0.2	1.2	0.3	0.7	0.1	0.6	0.1	1.9	0.1	1698	1.3	0.9
0.16	397	7.3	13	1.7	6.8	1.5	0.4	1.2	0.2	1.2	0.2	0.7	0.1	0.6	0.1	2.4	0.1	725	1.3	1
0.13	348	6.7	12	1.6	6.6	1.2	0.4	1.4	0.2	1.2	0.2	0.7	0.1	0.7	0.1	1.9	0.1	241	1.1	1
0.82	74	6.5	12	1.5	5.1	1.2	0.2	0.9	0.1	0.9	0.2	0.5	0.1	0.4	0.1	1.6	1	707917	2.2	0.7
0.09	169	6.8	13.1	1.7	6.8	1.1	0.3	1.4	0.2	1	0.2	0.7	0.1	0.7	0.1	3.9	0.3	354	1.4	1.2
0.18	163	4.2	7.9	1	3.7	0.8	0.2	0.8	0.1	0.6	0.2	0.5	0.1	0.4	0.1	1	0.1	1445	0.8	0.6
2.34	405	17.5	61.5	4.3	16.3	3.1	0.5	2.8	0.4	2.6	0.5	1.4	0.2	1.5	0.2	5.4	0.5	270987	7.3	2
0.48	462	11.1	17.4	2.7	11.5	2.1	0.5	1.9	0.3	1.9	0.4	1.2	0.2	1.2	0.2	2.7	0.2	73142	2.1	1.2

Appendix III trace element chemical compositions of samples analysed by LA-ICP-MS

Trace elements	Li	B	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb
WIJ 19	9.6	155.5	28.19	17	23.8	38.2	8869.3	2160.2	42.2	12.2	487	15	85.6	2.9	0.9	12300	59
WIJ 20	8.1	180.2	75.45	19	28.4	44.1	7731.9	711.9	34.9	11.1	621	13.2	99.1	3.4	2.7	7222	68
WIJ 21	6.3	157.7	61.66	17	20.2	35.3	112.1	51.2	15.8	8.2	638	12.4	91.2	3.2	2.7	20435	56
WIJ 22	5.7	168.8	21.93	12	8.6	12.9	206.2	56.2	15.6	8.5	449	6.9	53.1	1.9	1.2	32949	1976
WIJ 23	5.8	165.5	27.84	21	9.5	23.3	46.6	29.1	5.5	7.5	616	7.1	101.9	3.2	1.3	120874	95
WIJ 24	7.4	139.9	45.88	16	20.5	43.1	289.3	63.5	22.1	9.7	602	10.6	89.9	3.2	4.2	33842	130
WIJ 25	8.7	157.5	45.22	15	23.5	35.1	97.9	50.5	17.2	8.6	670	10.1	81.9	2.7	3.6	37943	248
WIJ 26	7.1	185.7	41.15	15	18.4	34	94.2	46	12.4	7.7	684	10.7	87.8	2.9	2.9	31212	63
WIJ 27	9.3	162.9	45.98	20	16.1	46.2	12288.1	2793	40.3	17.2	564	17.3	90	3.5	1.8	1600	157
WIJ 28	8.4	150	40.79	18	14.8	64.6	20931.5	11130.1	68.3	12.9	593	13.4	92.4	3.4	1.8	6040	265
WIJ 29	6.1	183.4	19.29	14	23	86.6	111970.5	1077.6	159.6	7.2	805	5.5	57.2	3.1	2.2	10200	15816
WIJ 30	5.7	165.5	29.89	21	8.7	53.2	21945.1	8389.6	47.7	7.3	502	7.7	103.3	3	1.4	822	72
WIJ 31	8.1	175.3	41.19	18	22.3	45.1	11701	8078.2	134.4	17.2	544	15.6	86.9	3.5	1.3	984	142
WIJ 32	6.8	120.9	19.43	16	6.3	17.5	124.6	39.6	23.4	11.4	325	6.9	77	2.6	0.6	39588	66
WIJ 33	8.2	77.1	17.88	18	5.9	24.2	4382.9	1309.7	97.2	11.4	204	6	76.7	2.6	0.5	67882	36
WIJ 34	34.9	21.4	79.96	6	88.4	30.5	2231.8	177.9	51.9	79.4	49	26	187	9.3	1.3	1548	74
WIJ 35	22.9	70.6	10.21	39	55.5	24.6	570.1	33	4.8	13.8	356	4.3	58.8	1.5	1.7	18	0
WIJ 36	6.8	182.4	43.01	17	7.9	23.1	66.5	31.4	8.3	7.1	800	9.5	86.5	3.2	5.5	7	170
WIJ 37	20.4	68.3	10.25	21	3.9	13	22.1	152.4	1.4	13.2	370	3.1	32.5	1.2	2	1	0
WIJ 38	5.9	159.2	16.92	13	3.6	5.6	16.6	11.8	2.9	6.1	536	6.8	73.7	2.5	0.7	2	51
WIJ 39	6.2	149.3	36.77	19	125.2	248.9	12078.9	6260.3	277.6	8.7	654	7.8	89.1	3.5	6	21208	298
WIJ 40	4.9	202.6	17.46	13	3.9	7.7	80	27	25	11.5	419	5.7	77.7	2.4	0.8	483	10121
WIJ 41	10.7	164.8	34.66	25	20	16.6	1208.3	126.5	19.2	9.7	466	8.4	106.8	3.1	2.2	513	1650
WIJ 42	3.5	48.3	6.99	11	3	22	21236.9	1192.3	37.7	7.1	480	7.1	40.7	1.6	0.1	5913	50
Wijk bij Duurstede (Dorestad) glass samples																	
LM 25	5.9	203.3	18	13	6.1	7.6	274.8	29.4	20.4	10.7	450	6.5	66.9	2.1	1.7	51	3575
LM 26	17.1	165	23	18	28.6	12.7	1143.8	107.5	11.4	20.6	467	7.3	75.3	2.5	2.1	295	1785
LM 27	12.8	144.2	19	14	13	25.7	33870.8	7164.7	202.2	17.6	408	6.2	66.1	2.2	1.8	558	2057
LM 28	8.4	149.2	19	15	8.7	8.5	412.8	97.5	12.4	10.4	425	6.3	70.1	2.2	1.4	96	1734
LM 29	12.5	124.9	20	17	16.9	12.4	2112	104.1	12.7	14.1	376	6.5	86.3	2.6	1.6	275	975
LM 30	18.7	130.4	17	15	580.5	25.6	1833.1	883.4	24.2	18.7	430	6.1	73.2	2.2	2.5	157	5703
LM 31	13.6	148	19	14	28	28.2	55184.7	15768.8	605.7	28.3	398	6.9	58.2	2.2	1.6	333	1859
LM 33	36	136.8	20	17	20.2	21.7	25129.6	2969.8	111.6	17.2	318	6.1	79.8	2.8	1.3	1994	1130
DOR 53	24	159.1	17.7	13.82	13	9.9	1708.3	90.6	14.1	14.1	469	6.6	59.5	2	1.7	230	2737
DOR 61	9.6	466.3	2.48	20.05	27.1	2.7	60.8	3693.2	58	70.3	25	3.6	138.9	1.2	0.7	18	495
DOR 66	15.2	145.1	18.73	15.28	22.3	11	1308.1	82.8	13	13	461	7	63.4	2.2	1.9	906	2122
DOR 90	16.8	153.8	22	17	17.4	13.6	3662.3	378.5	25	17.9	434	6.8	77.6	2.4	2	417	1352
DOR 91	5.6	199.8	17	13	6.6	8.6	199.6	30.3	22.6	10.1	450	6.3	64.9	2.1	1.8	57	3610
DOR 95	51	85.8	88.14	83.52	24.5	69	26.5	81.6	6.8	142.7	189	28.1	180.5	15.5	1.3	3	0
DOR 100	28.3	159.2	21	16	27.1	14.8	1789.2	115.7	13.7	18.3	463	7.5	76.6	2.6	1.9	977	2214
DOR 101	10.5	185.5	21	14	29.4	13.5	3542.6	101.6	28.6	15.3	470	6.6	65.2	2.4	1.8	579	4680
DOR 102	17.6	171.8	20	14	33.1	14.7	1332.6	92.1	18.1	16.6	465	6.7	62.4	2.3	1.9	674	2941
DOR 103	14.6	230.2	13	10	8.3	12	69.1	289	7.9	144.6	519	7.6	77.3	3.5	0.9	286	18
DOR 104	16.5	154.1	23	15	18.9	14	1765	691.8	14	16.7	482	7.4	68.2	2.6	2	495	1804
DOR 105	15.8	138.3	19	15	9.5	15.6	11995.6	3754	52.1	14.6	412	6.6	65.1	2.3	1.5	1614	1542
DOR 106	17.3	156.5	16	12	152	14.5	1005.1	62.5	9.1	11.5	482	6.9	51.7	1.9	2.6	1261	1451

Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
0.38	197	12.5	20.1	3	11.5	2.3	0.6	2.5	0.4	2.5	0.5	1.4	0.2	1.4	0.2	2	0.2	76928	1.6	1.3
0.23	247	13.6	16.3	3.2	13.3	2.6	0.7	2.9	0.4	2.3	0.5	1.4	0.2	1.3	0.2	2.3	0.2	30393	1.6	1.3
0.23	245	13.4	15	2.9	12.3	2.6	0.6	2.5	0.4	2.3	0.4	1.5	0.2	1.3	0.2	2.2	0.2	18301	1.5	1.3
0.18	215	7	11	1.7	6.8	1.6	0.3	1.1	0.2	1.2	0.2	0.7	0.1	0.6	0.1	1.4	0.1	17846	1	1.1
0.19	299	7.5	13.5	1.8	6.8	1.1	0.4	1.1	0.2	1.2	0.3	0.7	0.1	0.7	0.1	2.3	0.2	15019	1.4	1.3
0.38	306	11.4	14.6	2.4	9.6	1.9	0.5	2.2	0.3	1.8	0.4	1	0.1	1.2	0.2	2.3	0.2	269522	1.6	1.3
0.2	279	11	14	2.3	10.2	1.7	0.5	2.1	0.3	1.8	0.4	1.1	0.1	0.8	0.1	2.1	0.2	51806	1.3	1.3
0.11	288	11.3	14.7	2.5	10.9	2.2	0.6	2.2	0.3	1.9	0.4	1.2	0.2	1.1	0.1	2.1	0.2	38168	1.5	1.6
0.8	272	15.3	24.8	3.7	15.2	3.2	0.9	3.5	0.5	2.9	0.6	1.7	0.2	1.5	0.2	2.2	0.2	45749	2.3	1.6
0.43	296	11.7	18.3	2.7	11.8	2.6	0.6	2.6	0.4	2.4	0.4	1.3	0.2	1.1	0.2	2.4	0.2	58770	1.9	1.5
0.07	230	6.1	11.8	1.4	6.5	1.2	0.3	1.1	0.2	1.1	0.2	0.5	0.1	0.6	0.1	1.5	0.2	16703	1.4	0.7
0.17	325	7.2	12.9	1.7	7	1.3	0.3	1.3	0.2	1.3	0.3	0.8	0.1	0.9	0.1	2.7	0.2	43264	1.4	1.4
0.76	253	14	23.2	3.4	14.4	3.2	0.6	3.1	0.5	2.7	0.5	1.5	0.2	1.4	0.2	2.1	0.2	46027	2.1	1.5
0.52	143	7	12.9	1.6	7.4	1.5	0.4	1.4	0.2	1.3	0.3	0.7	0.1	0.7	0.1	2	0.2	416164	1.6	1
0.78	110	6.4	12.3	1.6	6.1	1.6	0.3	1.3	0.2	1	0.2	0.6	0.1	0.6	0.1	2.1	0.2	653466	1.6	0.8
5.6	1561	41.8	234.4	10.9	39.7	7.7	1.9	6.9	1	5.7	1	2.8	0.4	2.3	0.5	4.4	0.8	429979	12	3.3
0.13	125	4.5	7.7	1.1	3.7	0.4	0.1	0.7	0.1	0.7	0.1	0.5	0.1	0.4	0.1	1.3	0.1	344	1.2	0.5
0.1	263	9.4	14.1	2.2	9	1.9	0.5	2.1	0.3	1.7	0.4	1.2	0.1	0.8	0.1	2.2	0.2	74	1.5	1.2
0.23	121	3.2	6	0.7	3	0.4	0.1	0.7	0.1	0.4	0.1	0.4	0	0.4	0	1	0.1	2	0.9	0.6
0.03	186	6.9	11.7	1.5	7	1.2	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.8	0.1	23	1.2	1.2
0.14	325	7.6	13.8	2	7.1	1.4	0.5	1.3	0.2	1.6	0.2	0.7	0.1	0.7	0.1	2.1	0.3	71968	1.4	1.1
0.25	159	6.4	11.7	1.4	6.4	1.3	0.3	1	0.1	1.1	0.2	0.6	0.1	0.6	0.1	1.9	0.1	71267	1.5	1.1
0.22	362	8.5	14	2	8.3	1.8	0.4	1.5	0.2	1.3	0.3	1	0.1	0.7	0.1	2.4	0.2	4933	1.3	1.1
0.11	232	6.3	13.2	1.5	6.3	1.3	0.4	1.3	0.1	1.1	0.3	0.7	0.1	0.5	0.1	1.1	0.1	17115	0.8	0.6
0.16	264	6.8	11.8	1.5	6.2	1.2	0.3	1	0.2	1.1	0.2	0.7	0.1	0.5	0.1	1.7	0.1	1033	1.2	1.1
0.45	384	8.1	14.3	1.8	7.4	1.5	0.4	1.2	0.2	1.2	0.2	0.7	0.1	0.7	0.1	2	0.2	2119	1.3	1.1
0.39	284	6.5	12	1.6	6.3	1.2	0.4	1.1	0.2	1.1	0.2	0.6	0.1	0.5	0.1	1.8	0.1	3722	1.1	1
0.21	268	6.3	11.6	1.5	6.2	1.1	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.8	0.2	959	1.1	1
0.27	274	6.9	13	1.7	6.4	1.6	0.4	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	2.2	0.1	2182	1.3	1
0.31	237	6.7	12.4	1.5	6.1	1.3	0.3	1.2	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.6	0.1	1685	1.2	1
0.61	257	7.2	13.3	1.6	6.9	1.3	0.4	1.4	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.7	0.1	4782	1.3	1
2	260	6.7	13.2	1.6	6.3	1.3	0.4	1	0.2	1.1	0.2	0.7	0.1	0.5	0.1	2	0.2	4907	1.3	1.1
0.35	300	6.6	11.9	1.6	6.1	1.3	0.3	1.3	0.2	1.2	0.2	0.7	0.1	0.6	0.1	1.6	0.1	1775	1.2	1
0.29	114	3.4	6.9	0.8	2.8	0.5	0.1	0.6	0.1	0.5	0.1	0.4	0.1	0.4	0.1	3.8	0.1	5355	1.8	4.6
0.27	289	6.9	12.5	1.7	6.5	1.1	0.4	1.2	0.2	1.2	0.2	0.7	0.1	0.8	0.1	1.6	0.1	7806	1.3	1
0.31	336	7.3	13.4	1.7	6.8	1.2	0.4	1.4	0.2	1.1	0.2	0.7	0.1	0.6	0.1	2	0.2	2824	1.3	1
0.2	267	6.8	11.9	1.5	6	1.2	0.3	1.1	0.2	1	0.2	0.6	0.1	0.6	0.1	1.5	0.1	1130	1.1	1
10.25	603	34.5	69.7	8.3	30.7	6.3	1.5	5.8	0.8	5.1	1	2.7	0.4	2.6	0.4	4.9	1.1	19	11.2	2.8
0.4	328	7.6	14	1.8	7.4	1.5	0.4	1.3	0.2	1.3	0.2	0.8	0.1	0.7	0.1	2.1	0.1	6199	1.4	1.1
0.47	337	7.7	14.6	1.7	7.4	1.5	0.4	1.6	0.2	1.3	0.2	0.7	0.1	0.6	0.1	1.5	0.1	6311	1.4	1
0.35	305	7.1	12.9	1.6	7.2	1.4	0.4	1.2	0.2	1.1	0.2	0.7	0.1	0.5	0.1	1.6	0.1	5839	1.3	1
3.54	1506	71.5	93.2	8.8	27.5	2.6	0.5	2.2	0.3	1.4	0.2	0.7	0.1	0.6	0.1	2.2	0.3	1192	2.8	1
0.37	324	7.8	13.9	1.8	7.6	1.3	0.4	1.3	0.2	1.1	0.2	0.8	0.1	0.7	0.1	1.8	0.1	3801	1.4	1.1
0.27	310	6.7	12.9	1.7	6.6	1.4	0.3	1.2	0.2	1.2	0.3	0.7	0.1	0.6	0.1	1.7	0.2	11967	1.3	1
0.2	266	6.7	12.2	1.6	6.2	1.3	0.4	1.3	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.3	0.1	9092	1	1.1

Appendix III trace element chemical compositions of samples analysed by LA-ICP-MS

Trace elements	Li	B	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb
DOR 107	15.3	149.8	20	15	24.6	12.4	2092	120	18.2	15.9	451	7	67	2.5	1.7	752	2788
DOR 108	12.6	164.1	20	14	12.2	10.5	345.4	66.8	9.2	10.4	468	6.7	62.1	2.2	2.2	50	1336
DOR 109	21.5	146.5	17	14	15.5	10.4	669.5	76.9	9.3	12.9	463	6.9	56.5	2.1	1.5	271	1426
DOR 110	17.6	144.5	17.71	14.35	15.8	10.9	851.1	83.4	9.8	14.4	458	6.6	54.6	2.2	1.5	531	1796
DOR 111	14.7	139.6	23.41	18.74	36	39.8	4143.2	668.7	68	16.8	472	7.7	77.9	3.5	1.7	2441	1804
DOR 112	16.4	152.1	19.05	15.41	23.3	12.6	1613.8	111.5	15.6	13.5	464	7.1	66.6	2.3	1.5	732	2187
DOR 113	17.6	152.4	21.56	17.15	18.3	13.8	881	92	15.3	15.5	482	7.5	72	2.3	2	512	2115
DOR 115	39.9	152.2	23.55	19.11	9.1	12.3	634.5	126.6	9.6	24.9	479	7.2	85.6	2.6	2	306	1313
DOR 116	21.7	144.7	25.15	20.71	18.6	13	861.5	61.8	16	11.7	475	7.5	79.3	2.5	2.3	495	1313
DOR 117	30.1	154.2	21.16	18.55	28.7	13.1	1149.1	122.7	16.1	17.7	478	7.8	74.4	2.3	2	430	1973
DOR 118	9.6	150.4	15.37	14.09	9.3	8.5	460.5	46.6	10.2	13	446	6.4	56.2	1.9	1.4	116	1523
DOR 119	15.4	141.8	18.77	14.63	31.9	12.5	1215.8	100.6	17.5	13.9	455	6.7	61.6	2.2	1.8	746	2566
DOR 120	13	136.6	22.1	18.95	15.5	10.8	1130.2	202.8	17.8	17.1	410	6.9	82	2.3	1.7	604	1082
DOR 121	14.3	161	22.41	16.88	13.6	11.2	580.3	57.3	13.3	11.3	464	7	73.3	2.4	2.4	223	1934
DOR 122	17.9	99.9	20.57	24.32	6.7	10	273.7	97	4	8.8	267	6.8	153.2	3.5	0.8	28	285
DOR 123a	6.1	146.4	27.59	22.58	15.1	13.1	608.7	47.5	13.2	8.3	474	7.7	90	2.6	2.7	136	1456
DOR 123b	8.7	153.3	26.53	21.88	8.7	12.2	564.6	42.7	10.8	11.8	494	7.8	86.8	2.4	2.8	46	1200
DOR 124	7.3	141.2	20.48	13.55	7.4	9.7	240.7	41.2	8.1	13.8	436	7.4	52.4	1.9	2.2	34	1128
DOR 125	5.4	173.6	15.38	11.48	5	7.5	225.5	30.1	24	10	464	6.3	57.4	1.8	0.9	48	2856
DOR 126	4.8	196.4	17.37	13.52	5.6	7.5	216.6	29.9	22.4	12.4	422	6.5	69.1	2.1	1.6	51	4506
DOR 127	7.9	155.6	18.86	12.44	5.7	8.6	105.5	28.2	12.4	8.4	468	6.7	48.4	1.7	1.5	31	1853
DOR 128	9.7	176.7	18.05	11.65	5.8	7.9	128.5	28.6	15.4	8.5	443	6.4	52.8	1.6	1.7	40	2250
DOR 129	14.6	176.9	18.23	14.19	23.9	14	2142	130.5	20.6	14.4	429	6.4	60	2.2	1.6	903	2840
DOR 130a	17.7	192.8	16.53	12.69	7.9	8	417.3	48.5	12.8	15.4	372	6.4	61.5	1.9	1	115	2686
DOR 130b	16.3	191.7	20.18	15.53	305.1	28.4	1656	114.4	26.8	16.7	404	6.4	59.5	3.1	2.9	243	6909
DOR 131	8.1	198.5	11.05	10.1	7.2	5.8	673.5	44.2	23.6	8.5	398	5.7	46.5	1.7	0.5	164	3303
DOR 132	30.4	145.6	18.79	14.78	23.4	13.5	1045	104.5	9.8	18.6	441	8.2	66.9	2.4	1.6	1399	1418
DOR 133	13.9	169.3	18.33	13.75	19.8	13.4	1909.5	130.6	21.6	14.4	447	6.9	61.9	2	1.5	819	2486
DOR 134	6.2	191.7	19.53	13.34	22.8	19.4	6169.7	271	47	13.8	443	6.4	60.8	2.1	1.8	885	4673
DOR 135	14.7	167.2	20.54	16.2	18.2	12.4	1454	122.4	13.6	15.4	450	7.2	69.8	2.3	1.6	496	1658
DOR 136	8.9	350.6	6.87	8.9	8.5	5.6	45	240.3	16	132.1	443	6.5	69.6	2.6	0.4	2	16
DOR 137	16.4	165.9	19.38	14.69	21.3	11.6	1573.3	98.1	16.8	16.7	469	6.6	65.4	2.2	1.7	508	2935
DOR 138	15.1	161.9	19.26	15.45	22.7	13.7	2174.1	115.8	16.1	14.1	460	7.1	65.7	2.3	1.6	997	2447
DOR 139	29.6	168.7	19.4	15.6	5.9	9.2	372.2	84.3	13.1	19.1	395	7.4	72.5	2.3	1.2	220	2481
DOR 141	14.6	148.2	19.37	15.81	27.7	13.8	1490.6	108.9	16.6	15.9	471	6.9	64.4	2.3	1.6	1045	2746
DOR 142	12.5	166.1	18.76	14.43	31.9	12.2	4528.1	160.9	30.1	13.5	421	6.1	62.5	2.1	1.4	1076	5916
DOR 143	4.6	167.3	19.55	16.85	370.2	68.4	2440.5	99.4	27.5	9	451	6.6	70.8	2.2	5	276	4311
DOR 144	4.1	153.3	16.09	10.52	831.3	31.3	954	27.3	8.7	7.1	373	5.6	42.7	1.5	2	8	4735
DOR 145	4.3	160.8	15.54	11.71	336.5	20.6	1168.7	65	29.4	12.3	447	6.5	58.3	2	1.3	111	21027
DOR 146	5	139.9	9.01	8.26	11.8	8.9	24074.2	1279.3	102.4	6.4	383	5.6	35.8	1.6	0.2	960	15011
DOR 147	5.1	118	25.49	11.83	6.3	12.9	10658.5	65.9	37.9	14.2	480	6.7	50.4	1.9	1.9	105	13203
DOR 148	7	87.9	23.95	12.8	8.5	20.3	18352.8	79.7	32.5	11.2	536	7.4	44.4	1.8	3.3	772	5691
DOR 149	12.3	67.8	16.78	12.47	20.4	16.5	1582.8	81.7	20.9	13.1	305	5.4	50.6	2.3	1.2	36161	2250
DOR 150	31.7	75.9	35.26	32.64	8.3	15.4	331.4	1700.2	29	132.9	823	14.9	107.7	6.2	0.8	33	4175
DOR 151	66.4	88	36.72	31.51	8.4	17.3	171.2	1933.9	25.7	128.3	1203	17.3	143.7	8.8	0.8	9	4493

Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
0.33	289	7	13.6	1.6	7	1.4	0.4	1.2	0.2	1.2	0.2	0.7	0.1	0.6	0.1	1.8	0.1	7015	1.4	1.1
0.2	322	6.9	12.4	1.6	6.3	1.3	0.4	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.6	0.1	627	1.1	1
0.29	267	6.8	13.5	1.7	6.8	1.4	0.4	1.2	0.2	1.2	0.2	0.7	0.1	0.6	0.1	1.4	0.1	1405	1.2	1
0.27	268	6.7	12	1.7	6.6	1.2	0.4	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.4	0.1	3937	1.1	1
0.57	309	7.9	14.3	1.8	6.9	1.5	0.4	1.5	0.2	1.3	0.2	0.7	0.1	0.6	0.1	1.9	0.2	27064	1.6	1.1
0.3	290	7.2	12.4	1.5	6.8	1.4	0.5	1.3	0.2	1.2	0.2	0.7	0.1	0.7	0.1	1.6	0.2	5615	1.3	1.1
0.32	320	7.7	13.2	1.8	7.4	1.6	0.4	1.3	0.2	1.3	0.3	0.8	0.1	0.7	0.1	1.9	0.2	3616	1.3	1.1
0.4	405	7.7	13.5	1.8	7.2	1.4	0.4	1.2	0.2	1.3	0.3	0.6	0.1	0.7	0.1	2	0.2	1307	1.2	1
0.15	358	7.2	12.9	1.7	6.9	1.4	0.4	1.3	0.2	1.1	0.3	0.7	0.1	0.8	0.1	2	0.1	4322	1.2	1
0.34	370	7.3	13.7	1.7	7.2	1.2	0.4	1.5	0.2	1.2	0.3	0.7	0.1	0.7	0.1	2	0.1	3351	1.4	1
0.22	269	6.4	12	1.7	6.2	1.2	0.4	1.4	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.5	0.1	754	1	0.9
0.32	290	7.2	12.9	1.7	6.5	1.5	0.4	1.4	0.2	1	0.2	0.7	0.1	0.5	0.1	1.6	0.1	5727	1.3	1.1
0.29	299	7.5	13.4	1.7	6.7	1.4	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	2	0.2	2914	1.2	1.1
0.27	334	7.2	12.3	1.6	6.7	1.4	0.3	1.2	0.2	1.2	0.3	0.7	0.1	0.7	0.1	1.7	0.1	2149	1.1	0.9
0.08	277	7.1	13.5	1.6	6.8	1.2	0.4	1.5	0.2	1.1	0.2	0.6	0.1	0.8	0.1	3.6	0.2	461	1.5	1.2
0.17	408	7.5	12.8	1.7	6.7	1.2	0.4	1.5	0.2	1.3	0.3	0.7	0.1	0.8	0.1	2.1	0.1	1325	1.2	1
0.39	392	7.3	13.2	1.7	6.8	1.6	0.4	1.4	0.2	1.3	0.3	0.7	0.1	0.8	0.1	2.1	0.2	473	1.2	1
0.24	271	7.2	12.7	1.7	6.8	1.3	0.4	1.3	0.2	1.4	0.2	0.7	0.1	0.7	0.1	1.4	0.1	538	1.2	1
0.16	238	6.2	11.5	1.5	6.3	1.2	0.3	1.2	0.1	1.1	0.2	0.6	0.1	0.5	0.1	1.4	0.1	680	1.1	1.1
0.24	294	6.5	12.2	1.5	6.2	1.1	0.4	1.1	0.2	1.1	0.2	0.5	0.1	0.6	0.1	1.7	0.1	1915	1.4	1.2
0.22	300	6.1	11.3	1.5	6	1.1	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.7	0.1	1.1	0.1	509	0.9	0.9
0.22	253	6.3	11.1	1.4	5.9	1.2	0.3	1.1	0.2	1	0.2	0.5	0.1	0.5	0.1	1.4	0.1	422	0.9	0.9
0.31	262	6.3	11.7	1.5	6.1	1.1	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.5	0.2	8405	1.2	0.9
0.36	221	6.8	12.4	1.5	6.4	1.3	0.3	1.2	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.6	0.1	1437	1.3	1
0.34	230	7.3	13.1	1.7	6.6	1.2	0.3	1.1	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.6	0.2	2794	1.4	1
0.15	190	5.6	9.7	1.3	5.6	1.3	0.3	0.9	0.2	0.9	0.2	0.6	0.1	0.4	0.1	1.2	0.1	1315	0.9	0.8
0.48	292	8	14.4	1.9	7.5	1.4	0.3	1.6	0.2	1.4	0.3	0.8	0.1	0.7	0.1	1.7	0.2	4020	1.4	1
0.38	335	6.4	12.1	1.5	6.6	1.5	0.3	1	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.6	0.1	9054	1.2	1
0.33	267	6.9	12.4	1.5	6.5	1.5	0.3	1.3	0.2	1.2	0.2	0.7	0.1	0.5	0.1	1.5	0.1	10898	1.6	1
0.31	324	6.9	12.4	1.6	6.5	1.1	0.4	1.3	0.2	1.3	0.3	0.6	0.1	0.6	0.1	1.8	0.1	3840	1.2	1
2.24	1099	68	83	8.1	23.2	2.1	0.4	1.7	0.2	1	0.2	0.5	0.1	0.5	0.1	1.7	0.2	701	1.5	0.6
0.34	312	7.2	13	1.7	6.8	1.1	0.3	1.4	0.2	1.1	0.2	0.6	0.1	0.5	0.1	1.8	0.2	4250	1.4	1.1
0.31	302	7.1	13.3	1.7	6.7	1.3	0.4	1.4	0.2	1.3	0.2	0.7	0.1	0.5	0.1	1.6	0.1	8335	1.4	1
0.39	240	7.5	14.4	1.9	7.2	1.7	0.4	1.4	0.2	1.1	0.3	0.7	0.1	0.7	0.1	1.8	0.1	485	1.5	1.1
0.37	304	7.4	13.1	1.8	6.8	1.3	0.4	1.3	0.2	1.2	0.2	0.6	0.1	0.5	0.1	1.6	0.1	9728	1.3	1
0.31	259	6.7	12.2	1.5	6.3	1.3	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.6	0.2	12180	1.4	1.1
0.21	279	6.5	12	1.6	6.7	1.4	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.7	0.2	2844	1.1	1
0.1	212	5.4	10	1.2	5.5	1.2	0.4	1	0.1	1	0.2	0.6	0.1	0.5	0.1	0.9	0.1	177	0.9	1
0.32	223	7.1	13.3	1.7	6.6	1.4	0.4	1.4	0.2	1.1	0.2	0.5	0.1	0.6	0.1	1.3	0.1	5671	1.6	1.1
0.1	174	6.4	9.9	1.4	5.9	1.1	0.3	1.1	0.1	0.9	0.1	0.5	0.1	0.5	0.1	1	0.1	1335	1.1	0.9
0.29	272	7.5	13.3	1.7	6.5	1.5	0.4	1	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.4	0.1	2305	1.6	1.1
0.36	309	7.9	13.6	1.7	7.7	1.5	0.4	1.5	0.2	1.2	0.2	0.9	0.1	0.7	0.1	1.2	0.1	121308	1.3	1.1
0.42	206	5.9	10.3	1.3	4.9	1.1	0.3	1.2	0.2	0.9	0.2	0.6	0.1	0.5	0.1	1.3	0.2	488078	1.3	0.9
8.43	25021	25.9	41.3	5.4	20.8	3.7	1.2	2.9	0.4	2.4	0.5	1.4	0.2	1.3	0.2	2.7	0.6	263859	6	6
8.58	22165	34.2	58.8	7.1	26.5	5	1.6	4.2	0.5	3.1	0.6	1.6	0.2	1.5	0.2	4.4	1	288731	12.8	7.4

Appendix III trace element chemical compositions of samples analysed by LA-ICP-MS

Trace elements	Li	B	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb
Deventer glass samples																	
DEV 1	52.5	415.5	59.57	79.22	12.8	41.8	29.8	68.5	18.6	190.5	402	18.4	180	12.5	1.6	2	1
DEV 2	5.9	114	22.93	14.77	411.8	44.1	724.6	26.7	5.1	7	580	7.1	76.3	2.5	3.7	17	5
DEV 3	10.3	155	17.24	12.94	9.4	8.3	844.9	294.1	20.6	15.2	429	6.5	62.4	2	1.6	127	1669
DEV 4	10.5	43.3	12.72	11.98	19.3	19.7	85.8	76.1	29.1	31.3	382	3.3	56.2	2.5	1.7	1	1050
DEV 5	17.7	118.7	11.71	6.42	14.5	27.8	303.8	127	63.5	65.1	466	4.9	33.4	1.3	2.3	13	2
DEV 6	14.5	262.3	15.7	17.37	6.9	9.8	45.8	329.1	2.8	179.1	410	10.4	140.7	4.8	0.3	1	4
DEV 7	12.9	226.4	19.46	24.05	5.3	11.6	44.5	260.2	3	191.7	377	11.4	192	6	0.2	1	3
DEV 8	13.8	215.6	7.21	8.92	6	8.1	56.7	332.9	1.1	119.5	682	3.9	71.3	2.7	1.7	1	1
DEV 9	6.9	44.4	5.55	168.08	2.9	4.5	8.9	27.9	24.6	10.9	182	2.6	107.8	1.5	0.2	6	3
DEV 10	31.4	137.6	19.35	19.95	12.1	11.1	1017.9	108.2	5.5	23.5	335	6.5	113.8	2.8	1.1	323	759
DEV 11	6.2	89.5	21	24.08	10.1	8	487.9	82.6	6.4	7.7	253	6.9	158.4	3.8	0.4	121	117
DEV 12	11.4	155.8	21.24	17.56	8.7	9.7	508.5	45.9	12.7	13	429	6.9	73.8	2.4	2	74	1314
DEV 13	49.9	174.2	21.57	14.67	8.5	31.8	112.3	411.4	74.2	295	916	10.6	149.5	4.4	1.7	90	45
DEV 14	28.3	190.4	19.9	18.97	7.3	20.8	412.1	161.3	2	206.3	269	11.1	189.7	5.4	0.5	29	0
DEV 15	18.1	123.5	17.77	26.31	4.1	24.8	121.7	442.1	0	174	281	9	145.8	4.6	3.4	10	0
DEV 16 weathered	0	118.2	5.27	20.08	6.5	23.7	382.9	274.7	6.5	65.9	113	9.8	143	3.7	0.3	35	1
DEV 17 weathered	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DEV 18	52.3	169.2	16.22	17.27	10.9	18.2	1619.7	191.8	6.3	124.5	416	8.9	122.9	3.9	2	261	595
DEV 19	20.5	143.2	22.87	19.78	16.2	13.5	677.5	72.9	11.1	14.5	427	7.1	91.9	2.8	2.4	389	1091
DEV 20	12.2	182.1	33.84	14.79	5.2	15.1	46.2	28.7	5.5	6	456	7.8	64.6	2.1	2.1	2	38
DEV 21	10.9	191.1	19.34	27.27	6.1	17.2	57	257.7	1.8	96.1	606	9.8	192.5	6.9	1.8	1	0
DEV 22	14	58.3	7.32	10.66	7.8	7.4	40.8	68.8	14.4	34.1	371	3.6	54.6	2.3	1	1	194
DEV 23 weathered	13.7	46.1	7.96	8.16	4.5	4.4	34	43.1	5.1	16.3	102	3.1	88.5	5.7	0.5	2	34
DEV 24	24.3	245.4	10.25	10.85	42.5	46.2	87.1	462.9	2.2	38.9	782	4.9	70.4	3.7	0.6	1	0
DEV 25	10.8	63.1	8.6	7.29	3.2	6.9	95.3	87.2	6.9	22.2	260	3.1	66.7	2.3	1.1	3	121
DEV 26	35.4	120.1	6.71	6.54	1.5	9.5	21901.8	169	7	362.4	455	2.7	70.4	1.4	1	55	2
DEV 27	15.3	178.3	22.89	26.95	7.1	37.6	75.2	244.8	1.7	233.4	373	11.8	190.9	6.1	4.1	5	1
DEV 28	13	260.9	15.65	17.05	7	11.1	45.8	324	2	181.2	410	9.5	124.6	4.3	0.2	1	0
DEV 29	28	172.3	17.78	21.22	7.7	19.6	59.2	295.6	1.1	109.5	892	7.5	142.2	5.5	1.7	1	0
DEV 30a	16.2	173	8.8	6.08	49.1	38.6	85.4	321	48.3	354.7	1058	6.6	161.6	3.3	0.5	7	1
DEV 30b	0.2	18.2	15.31	9.69	40.7	40.3	115.8	716.8	41.7	112.9	240	11.3	273.5	5.3	2.3	11	2
DEV 31	50.1	92.2	19.82	25.1	7.7	9	372.5	48.9	2.3	10.6	238	6.4	155.6	3.6	0.3	111	130
DEV 32	9.3	228.3	6.21	10.14	4.7	16.4	85.7	206.8	0.6	190.3	360	3.5	89.6	2	2.9	11	0
DEV 33	8.1	251.9	7.93	13.57	5.1	14.8	69.4	164.4	0.8	170.6	218	3.5	65.3	1.7	2.5	2	0
DEV 34 weathered	29.4	1951.6	14.89	2391.84	0	14.9	7.4	1669.2	89.8	1.3	1	0	0	0	0	126	36
DEV 35	15.8	263.3	4.19	6.02	3.3	10.6	59.5	268.5	1.4	431.8	993	2.8	71.7	1.1	0.8	1	0
DEV 36	43.7	166.1	7.79	10.58	3.3	12	780.8	213.6	2.3	331.5	417	3.2	76.4	1.7	2.7	37	1
DEV 37	11.7	107.1	9.99	9.01	2.7	7.7	25.5	76.5	4.7	10.2	264	5.7	129.9	2.5	0.9	5	3
DEV 38	19.9	160.3	5.31	5.98	1	4.6	158.3	187.8	2.1	306.4	583	1.8	56.7	1.3	0.9	5	1
DEV 39	22.8	168.4	17.97	19.81	5.7	14.7	49.2	196.2	1.4	167.7	339	9.3	127.6	5	8.2	1	0
DEV 40a	19	87.6	18.93	23.8	8.1	11.5	21560.9	80.5	5.3	12.6	235	6.1	145.3	3.4	0.5	156	175
DEV 40b	10	89.1	20.87	25.05	8.9	8.4	837.6	71.3	5.1	11.2	269	6.8	157.3	3.7	0.3	258	137
DEV 41	12.4	127.1	15.87	15.39	12.7	15.4	21451.4	113	35.3	36.3	366	6.6	96	2.8	1.1	201	928

Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
2.5	370	27.2	67.8	6.2	23.6	4.5	1.1	4.8	0.6	3.6	0.8	2	0.3	1.8	0.3	5.2	0.7	12	10.9	2.6
0.09	280	6.8	11.6	1.6	6.3	1.4	0.4	1.2	0.2	1	0.2	0.6	0.1	0.7	0.1	1.9	0.2	442	1.1	1.1
0.22	287	7.6	12.6	1.7	6.7	1.4	0.3	1.3	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.5	0.1	1323	1.2	1
0.38	960	5.1	9.6	1.1	4.2	0.8	0.3	0.8	0.1	0.6	0.1	0.4	0.1	0.3	0.1	1.4	0.2	31684	0.9	3
0.39	582	4.8	6.6	1	4.3	1.2	0.2	0.9	0.1	0.8	0.1	0.5	0.1	0.4	0.1	0.9	0.1	70	1.1	2
1.24	958	45.1	58.7	6.5	20.6	3	0.5	2	0.3	1.8	0.4	1.1	0.1	1.1	0.1	3.7	0.3	5	3	0.9
1.22	902	38.6	50.8	5.5	18.9	2.7	0.5	2.5	0.4	2.1	0.5	1.3	0.2	1.2	0.2	5.4	0.4	8	4	1.1
0.99	1647	10.4	16.9	1.6	5.3	0.7	0.2	0.6	0.1	0.6	0.1	0.5	0.1	0.4	0.1	1.9	0.2	3	1.1	0.4
0.22	251	3.9	10.8	0.7	2.6	0.4	0.1	0.5	0.1	0.3	0.1	0.3	0	0.2	0.1	2.8	0.1	60	0.8	0.6
0.53	341	10.3	16.3	1.8	7.9	1.5	0.3	1.3	0.2	1.1	0.2	0.8	0.1	0.6	0.1	2.9	0.2	1349	1.6	1
0.23	182	7.4	13.5	1.7	6.5	1.3	0.4	1.1	0.2	1.1	0.3	0.8	0.1	0.7	0.1	3.8	0.3	842	1.5	1.1
0.19	392	7.6	12.7	1.7	6.7	1.4	0.3	1.1	0.2	1.2	0.3	0.6	0.1	0.5	0.1	1.7	0.1	650	1.2	1
1.82	4829	12.2	24.9	2.9	10.9	2.2	0.8	1.8	0.3	1.6	0.4	1.1	0.2	1.1	0.1	3.9	0.3	394	4.5	2.5
1.2	1075	39.5	54.3	5.4	17.5	2.7	0.4	2.1	0.3	1.8	0.4	1.3	0.2	1.3	0.1	4.8	0.4	16	4.2	1.1
1.93	1082	13.8	24.1	2.9	10.6	1.7	0.5	1.9	0.2	1.7	0.3	1	0.2	1	0.1	3.7	0.4	88	3.5	1
0.45	359	16	30.7	3.6	12.6	2.2	0.6	1.9	0.3	2	0.5	1.5	0.1	0.8	0.1	3.4	0.4	29	5.3	0.6
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.19	863	29.7	34.8	4.5	14.8	2	0.4	2	0.3	1.5	0.3	1	0.1	0.9	0.1	3.3	0.3	984	2.4	0.9
0.26	428	7.6	13.2	1.8	6.7	1.3	0.4	1.5	0.2	1.3	0.3	0.8	0.1	0.7	0.1	2.3	0.2	2035	1.3	1
0.06	235	7.6	11.5	1.7	7.1	1.4	0.3	1.5	0.2	1.4	0.3	0.8	0.1	0.8	0.1	1.5	0.1	37	1.1	0.9
1.6	2243	20.7	36.2	3.7	12.8	1.8	0.5	1.7	0.2	1.6	0.4	1	0.2	1.1	0.2	4.9	0.5	6	3.2	1.1
0.33	419	4.4	7.7	0.9	3.9	0.8	0.2	0.7	0.1	0.5	0.1	0.3	0	0.4	0.1	1.3	0.1	28453	0.9	0.9
0.26	190	6.1	11.3	1.3	4.7	0.8	0.2	0.6	0.1	0.6	0.1	0.4	0	0.4	0.1	2	0.3	70	1.6	0.8
0.34	3273	10.2	14.8	1.6	5.7	1	0.4	0.9	0.2	0.8	0.2	0.4	0.1	0.4	0	1.9	0.2	4	1.8	0.6
0.52	321	4.4	7.5	0.9	3.5	0.6	0.2	0.5	0.1	0.4	0.1	0.3	0.1	0.3	0	1.8	0.2	138	1.3	1
3.55	1273	3.6	7	0.8	2.8	0.5	0.2	0.4	0.1	0.4	0.1	0.3	0	0.3	0	1.7	0.1	521	1	0.3
1.55	1243	36.2	39.5	5.8	19	2.6	0.6	2	0.3	2.1	0.5	1.2	0.2	1.2	0.2	5.1	0.4	26	3.4	1.1
1.22	939	45.7	57.7	6.5	22	2.8	0.6	2.5	0.3	1.5	0.3	1	0.1	0.8	0.2	3.3	0.3	4	2.7	0.9
1.28	1761	14.3	26.2	2.7	8.7	1.3	0.4	1.2	0.2	1.2	0.3	0.8	0.1	0.8	0.2	3.9	0.3	4	2.4	0.8
1.52	5423	12.2	32.3	2.8	11.5	2.2	0.8	1.6	0.2	1.2	0.3	0.7	0.1	0.6	0.1	4.3	0.2	38	4.6	1.8
0.48	3473	20.8	55.4	4.8	17.6	3.1	0.9	3.2	0.4	2.1	0.4	1	0.2	1.1	0.1	7.9	0.4	68	7.4	2.8
0.22	189	6.6	13.1	1.5	6.6	1.3	0.4	1.4	0.1	1	0.2	0.7	0.1	0.6	0.1	3.8	0.2	795	1.4	1.1
1	1124	21.4	17.9	2.3	7.5	0.8	0.2	0.6	0.1	0.6	0.1	0.3	0.1	0.3	0.1	2.5	0.1	3	1.1	0.3
0.65	663	60.5	40.1	6.6	20.6	1.7	0.2	1.1	0.1	0.6	0.1	0.3	0	0.3	0.1	1.5	0.1	3	1	0.3
0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	3	0.8	0
4.31	2718	6.2	9.5	1	3.5	0.4	0.3	0.4	0.1	0.5	0.1	0.3	0	0.3	0	1.9	0.1	4	0.9	0.3
2.75	1332	14.5	15.4	1.9	7.2	0.6	0.2	0.7	0.1	0.6	0.1	0.4	0.1	0.4	0.1	2.1	0.1	155	1.2	0.4
0.16	106	9.3	16.5	2.1	7.3	1.6	0.3	1.4	0.2	1.1	0.2	0.6	0.1	0.5	0.1	3.2	0.2	58	2.4	0.7
3.31	1350	3.2	6.1	0.6	2.1	0.4	0.2	0.3	0.1	0.3	0.1	0.2	0	0.3	0	1.3	0.1	50	0.8	0.3
1.16	605	24.5	44.7	4.3	15.1	2.2	0.4	2	0.3	1.5	0.3	0.9	0.1	0.9	0.1	3.2	0.3	3	2.6	0.8
0.29	186	7	13.2	1.6	6.2	1.2	0.3	1.3	0.2	1.2	0.2	0.7	0.1	0.7	0.1	3.4	0.3	931	1.4	1.1
0.23	203	7.2	13.9	1.6	6.5	1.3	0.3	1.3	0.2	1.1	0.2	0.8	0.1	0.6	0.1	3.8	0.2	1681	1.6	1.2
0.34	350	9.6	16	1.9	7.2	1.3	0.3	1.2	0.2	1.2	0.2	0.7	0.1	0.7	0.1	2.4	0.2	1913	1.5	1

Appendix III trace element chemical compositions of samples analysed by LA-ICP-MS

Trace elements	Li	B	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb
Susteren glass samples																	
Sust 1 (bead body)	6.5	139	11.6	11.3	138.7	24.5	9010	1638	22.3	8.7	461	6.6	47.3	1.7	1.2	1947	3471
Sust 2 (bead body)	10	150.7	17.8	14.1	16.3	12.3	1879.3	99.3	15	12.3	417	7.2	65.1	2.2	1.8	684	1988
Sust 2 (decoration)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sust 3 (bead body)	17.5	120.7	18.7	46.4	974	34	1180	3990	23.5	13.8	506	5.7	98.6	2.4	2.3	3223	505
Sust 3 (decoration)	14.6	147	25.2	21.5	20.1	28.3	1580.7	114.2	19.1	14.2	432	8.4	91.7	3.7	2.2	96733	3357
Sust 4 (bead body)	16.1	142.6	19.3	19.7	50	13.7	1279.7	247.6	12.4	14.7	445	7	74.1	2.2	1.7	570	1635
Sust 4 (decoration)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sust 5 (bead body)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sust 5 (decoration)	10	166.9	21.7	18.7	13.5	13.1	947.3	81.2	16.1	12.6	428	7.6	80.6	2.6	2.1	9195	2488
Sust 6 (bead body)	15.8	159.3	20.2	16.5	14.8	11.7	1569	94.1	13.4	14.9	471	7.4	75.6	2.4	2	625	2127
Sust 6 (decoration)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sust 7	6.4	187.4	13.9	11.9	327	28.2	2173.3	64.8	33.4	9.2	404	6.1	57.9	1.9	2.4	148	10020
Sust 8	5.5	183.7	13.2	11.2	322.3	25.7	1887.7	57.1	32.9	7.5	399	6	52.8	1.7	2.3	131	10253
Sust 9	11.6	169.7	22.9	17.8	51.9	24	22100	339.7	28.6	17.9	406	7.2	74.9	3.4	2.2	1690	3597
Sust 10	10.6	163	17	14.2	5.1	7	117.7	45.9	13.9	11.5	432	6.6	68.5	2	1.7	162	2492
Sust 11	14.2	189.9	25.4	24	11.3	16.1	82.9	257.9	2	398.3	303	12.2	226.6	7.6	0.4	11	4
Sust 12	12.6	132.1	22.7	21.5	22.9	13.4	1867.3	168.3	13.2	18.1	411	6.5	93.1	3.1	1.6	944	1072
Sust 13	14.2	138.9	19	25.1	35.9	15.5	1888.3	127.3	15.9	15.3	451	5.9	72.7	2.2	1.8	484	2078
Sust 14	16.6	132.2	21.2	21	22.2	12.8	2057	114.4	11	18.1	386	7.4	99.2	2.9	1.7	394	1198
Sust 15	6.6	154.1	18.4	13.8	53.9	14.5	6090	118.6	29	13.4	394	6.8	60.8	2.3	1.5	1082	6810
Sust 16	22.2	138.3	22.2	25.2	24.9	16	1159.7	106	13.5	24.5	402	8.3	97	3.2	1.6	557	1682
Sust 17	14.6	171.5	15.5	12.3	419	35.4	2139	94.6	29	61.1	431	5.9	51.5	1.9	2.9	498	9703
Sust 18	17.7	141	74.4	38	14.2	21.1	4906.7	190.8	8.2	106.6	290	11.2	169.6	19.2	2.3	668	1276
Sust 19	12.1	179.2	16.5	14.2	27	13.3	2070	190	13.5	152.3	396	7.1	90.5	3.3	1.1	628	1990
Sust 20	5	156.3	19.2	12.7	13.9	11.6	2463.3	66.3	21.8	12.2	443	5.9	53.4	2	1.9	279	2423
Sust 21	15.4	127.9	22.3	21	22.9	13.8	1722.3	136.1	11.4	16.2	407	7.1	90.6	2.7	1.5	642	1221
Sust 22	9.4	161	18.6	14.8	30.1	12.2	2264	116.3	17.9	12.3	460	6.4	58.8	2.2	1.6	597	2990
Sust 23	11.5	147.2	19.3	15.3	22.6	12.7	1597.7	119.3	15	13.2	455	7.1	63.6	2.2	1.7	670	2095
Sust 24	6.5	154.5	13.3	11.4	513.3	32.2	1585.7	64.8	31.1	11.9	421	6.4	45.5	1.7	2.4	559	13767
Sust 25	30.7	160.7	40.7	41	11	16.3	111.7	44.1	5.4	15.5	495	9.4	161.4	4.4	4	61	260
Sust 26	12.1	160.5	22.8	18	20.6	14.2	2322	127	20.1	12.3	461	6.7	71.5	2.4	2.2	673	2499
Sust 27	13.7	144.1	20.4	18.8	23.7	13.5	1282.3	107.7	11	19.1	451	7.2	71.7	2.3	1.9	563	1723
Sust 28	22.1	115.6	17.3	46.4	25.7	19.4	415.3	126.1	25.4	13.9	503	4.9	92.9	2.1	1.9	252	426
Sust 29	9.3	165.4	21.5	16.4	19.3	15.8	3163.3	187.2	41.2	13.6	456	6.6	66.2	2.5	2	876	3287
Utrecht glass samples																	
Utr 77	2.3	151.7	14.98	14.55	246.3	80.4	904	22.3	8.5	6.3	406	7.3	72.9	2.7	3.3	404	70
Utr 78 modern	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Utr 79	9.8	105	12.93	863.06	0.8	13.2	3.6	11.8	15.3	12.2	58	8	115.9	1.6	0.4	2	0

Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
0.12	224	6.5	11.3	1.4	5.8	1.3	0.3	1.1	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.2	-	6687	0.9	0.7
0.28	274	6.8	12	1.5	6.2	1.2	0.3	1.3	0.2	1.2	0.3	0.7	0.1	0.6	0.1	1.7	-	5260	1.2	0.9
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.35	201	7.6	14.4	1.7	6.3	1.2	0.3	1.1	0.2	1.1	0.2	0.6	0.1	0.5	0.1	2.6	-	2246	1.7	0.9
0.77	430	8.7	16	2	7.8	1.6	0.4	1.5	0.2	1.4	0.3	0.9	0.1	0.8	0.1	2.5	-	868333	1.8	1.1
0.3	293	7.3	12.8	1.6	6.4	1.3	0.3	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.9	-	3800	1.4	1
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.35	357	7.2	12.6	1.6	6.4	1.4	0.4	1.3	0.2	1.2	0.3	0.7	0.1	0.6	0.1	1.9	-	175333	1.3	1.1
0.31	312	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	7.3	13.3	1.7	7	1.2	0.4	1.3	0.2	1.3	0.2	0.7	0.1	0.7	0.1	1.9	-	5003	1.3	1.1
0.15	205	6.7	11	1.4	5.9	1.2	0.3	1.1	0.1	1.1	0.2	0.6	0.1	0.5	0.1	1.5	-	1862	1.1	1
0.14	194	6.5	10.9	1.4	5.4	1.1	0.3	1.1	0.2	1	0.2	0.6	0.1	0.5	0.1	1.4	-	2150	1.1	1
0.83	255	8.2	14.9	1.7	7	1.5	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.9	-	11550	1.8	1.1
0.28	252	6.4	11.5	1.5	5.8	1.2	0.3	1.3	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.7	-	614	1.1	1
1.75	1107	37.3	64.3	5.9	19	2.9	0.5	2.4	0.3	2.1	0.4	1.2	0.2	1.2	0.2	5.8	-	28	5	1.5
0.37	358	8.3	14.9	1.9	7	1.3	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.7	0.1	2.3	-	4760	1.4	1.1
0.35	291	7.1	13.3	1.6	6.4	1.2	0.3	1.1	0.2	1	0.2	0.6	0.1	0.5	0.1	1.9	-	4397	1.3	1
0.32	349	8.5	14.9	1.8	7.3	1.3	0.4	1.3	0.2	1.1	0.3	0.7	0.1	0.7	0.1	2.5	-	3657	1.4	1.1
0.45	235	7.8	13.5	1.6	6.7	1.3	0.3	1.3	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.5	-	12260	1.3	0.9
0.87	310	9.5	18.5	2.2	8.7	1.7	0.4	1.6	0.2	1.4	0.3	0.9	0.1	0.8	0.1	2.5	-	5157	2.2	1.1
0.54	276	6.7	11.9	1.5	6	1.2	0.3	1	0.2	1	0.2	0.6	0.1	0.5	0.1	1.3	-	6350	1.1	1
2.97	357	13.8	27	2.7	8.9	1.7	0.5	1.6	0.3	1.8	0.4	1.3	0.2	1.3	0.2	4.6	-	302	5.8	2.9
1.68	803	28.5	41.2	4.2	13.4	1.9	0.4	1.4	0.2	1.2	0.3	0.7	0.1	0.6	0.1	2.3	-	4973	2.3	1
0.3	320	6.7	12.2	1.5	6.1	1.2	0.3	1.1	0.2	1.1	0.2	0.6	0.1	0.5	0.1	1.3	-	4217	1.2	1
0.38	318	8	14	1.8	7	1.4	0.4	1.4	0.2	1.1	0.3	0.7	0.1	0.7	0.1	2.2	-	3250	1.4	1.1
0.3	275	7	12.4	1.6	6.3	1.4	0.4	1.2	0.2	1.1	0.2	0.6	0.1	0.5	0.1	1.5	-	6760	1.2	1
0.35	288	7	12.9	1.7	6.4	1.3	0.3	1.2	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.7	-	4950	1.3	1.1
0.26	226	6.9	10.8	1.4	5.7	1.2	0.3	1.2	0.2	1	0.2	0.6	0.1	0.5	0.1	1.2	-	6077	1	0.9
0.34	1736	8.9	16.3	2.1	8.5	1.8	0.5	1.6	0.3	1.6	0.3	1	0.1	0.9	0.1	4	-	315	1.8	1.3
0.32	351	7.2	13	1.6	6.4	1.4	0.4	1.2	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.8	-	5890	1.3	1.1
0.43	345	7.6	13.4	1.7	6.8	1.5	0.3	1.3	0.2	1.2	0.2	0.6	0.1	0.6	0.1	1.8	-	3856	1.3	1
0.25	207	6.9	13.3	1.6	6.2	1.1	0.3	0.9	0.1	0.8	0.2	0.5	0.1	0.5	0.1	2.4	-	10567	1.4	0.8
0.37	299	7.2	12.8	1.6	6.4	1.3	0.4	1.3	0.2	1.1	0.2	0.7	0.1	0.6	0.1	1.7	-	11330	1.3	1
0.06	183	6.7	12.1	1.5	6.1	1.3	0.3	1	0.2	1.1	0.2	0.6	0.1	0.6	0.1	1.9	0.2	4035	1.2	1.3
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.36	318	5.5	12.3	1.3	5.2	1.3	0.3	1.5	0.2	1.4	0.2	0.9	0.1	0.8	0.1	2.9	0.1	93	2.9	0.6

Appendix IV photos of the samples from Maastricht and Utrecht

Figure appendix IV.1 Photo MABRO 1, Mabro, Maastricht, rim fragment of crucible with white 'frit-like' material adhering.

Figure appendix IV.2 Photo MABRO 2, Mabro, Maastricht, Crucible fragment with colourless and white/yellow material attached.

Figure appendix IV.3 Photo MABRO 3, Mabro, Maastricht, small crucible fragment with green and weathered opaque yellow pigment.

Figure appendix IV.4 Photo MABRO 4, Mabro,Maastricht, rim fragment of crucible with colourless glass on inside.

Figure appendix IV.5 Photo MABRO 5, Mabro,Maastricht, rim fragment of crucible with colourless vitreous material on inside white 'frit-like' material adhering to both sides.

Figure appendix IV.6. Photo MABRO 6, Mabro, Maastricht, base fragment of crucible with opaque yellow pigment adhering.

Figure appendix IV.9 Photo MABRO 9, Mabro,Maastricht, small crucible fragment with deep translucent glass on the inside.

Figure appendix IV.7 Photo MABRO 7, Mabro,Maastricht, small red fragment of crucible with natural green glass adhering to both sides.

Figure appendix IV.10 Photo MABRO 10, Mabro,Maastricht, red base fragment of crucible with green vitrification on lower side.

Figure appendix IV.8 Photo MABRO 8, Mabro,Maastricht, red fragment of crucible base with opaque yellow outside and colourless-green glass adhering on the inside.

Figure appendix IV.11 Photo MAJO 1, Jodenstraat, Maastricht, red base fragment of crucible with opaque yellow pigment adhering (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.14. Photo MAJO 4, Jodenstraat, Maastricht, base fragment of crucible with white residue adhering (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.12. Photo MAJO 2, Jodenstraat, Maastricht, crucible base of grey fabric with weathered opaque yellow pigment and translucent residue adhering (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.15 Photo MAJO 5 (inside), Jodenstraat, Maastricht, base of crucible with opaque yellow glass adhering (MAJO= Jodenstraat, Maastricht).

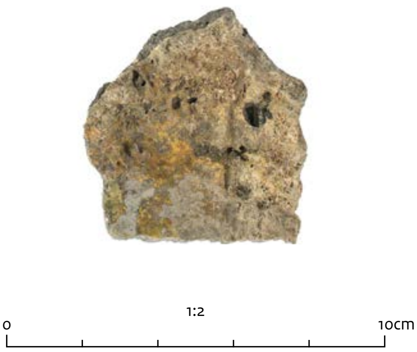


Figure appendix IV.13 Photo MAJO 3, Jodenstraat, Maastricht, base fragment of crucible with weathered opaque yellow pigment adhering (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.16 Photo MAJO 5 (outside), Jodenstraat, Maastricht, base of crucible.

Figure appendix IV.17 Photo MAJO 6, Jodenstraat, Maastricht, base fragment of crucible with opaque yellow glass on inside (MAJO= Jodenstraat, Maastricht).

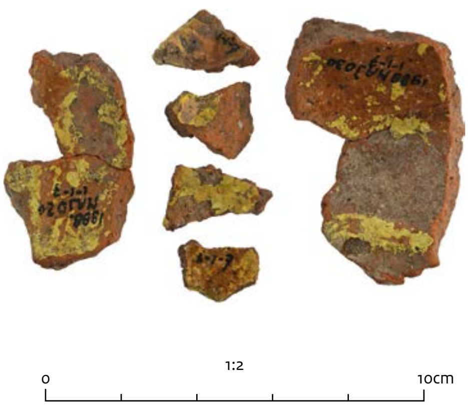


Figure appendix IV.18 Photo MAJO 7, Jodenstraat, Maastricht, base of crucible with opaque yellow glass adhering (MAJO= Jodenstraat, Maastricht).

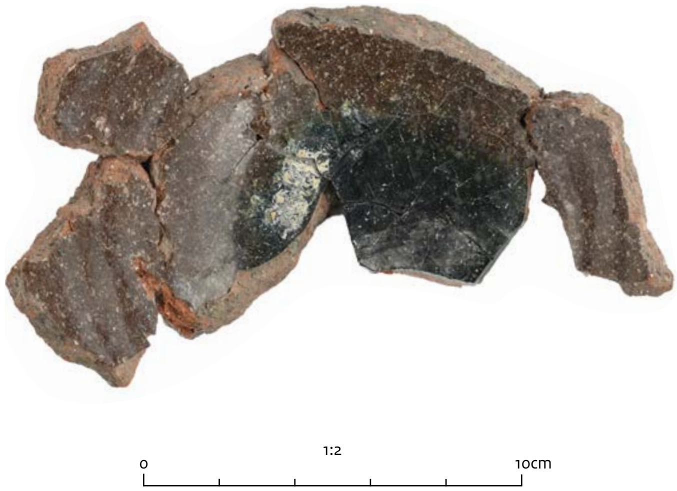


Figure appendix IV.19 Photo MAJO 8, Jodenstraat, Maastricht, base of crucible with dark translucent glass adhering (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.20 Photo MAJO 9, Jodenstraat, Maastricht, possible brick fragment with opaque yellow and white residue adhering (MAJO= Jodenstraat, Maastricht).

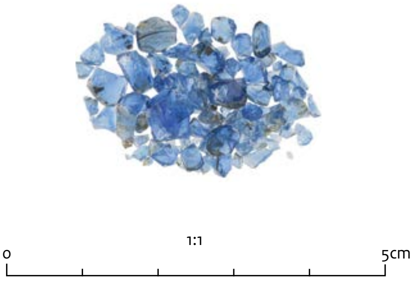


Figure appendix IV.21 Photo MAJO 10, Jodenstraat, Maastricht, blue fragments of glass (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.24 Photo MAJO 13, Jodenstraat, Maastricht, scrap of green glass (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.22 Photo MAJO 11, Jodenstraat, Maastricht, scrap of red glass (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.25 Photo MAJO 14, Jodenstraat, Maastricht, yellow-green window glass (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.23 Photo MAJO 12, Jodenstraat, Maastricht, scrap of red glass (MAJO= Jodenstraat, Maastricht).

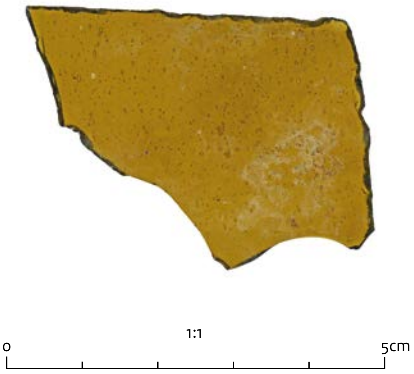


Figure appendix IV.26 Photo MAJO 15, Jodenstraat, Maastricht, yellow-green window glass (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.29 Photo MAJO 18, Jodenstraat, Maastricht, weathered yellow drop (MAJO= Jodenstraat, Maastricht).

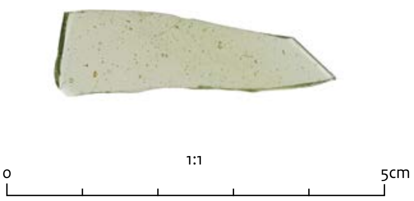


Figure appendix IV.27 Photo MAJO 16, Jodenstraat, Maastricht, pale yellow-green window glass (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.30 Photo MAJO 19, Jodenstraat, Maastricht, red glass drop (MAJO= Jodenstraat, Maastricht).

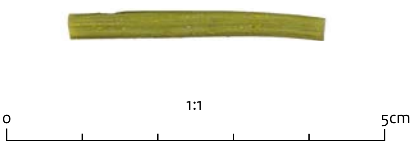


Figure appendix IV.28 Photo MAJO 17, Jodenstraat, Maastricht, thin green glass rod (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.31 Photo MAJO 20, Jodenstraat, Maastricht, dark green glass drop (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.32 Photo MAJO 21, Jodenstraat, Maastricht, milky blue pulled rod (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.33 Photo MAJO 22, Jodenstraat, Maastricht, thin red rod (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.34 Photo MAJO 23, Jodenstraat, Maastricht, twisted opaque white rod (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.35 Photo MAJO 24, Jodenstraat, Maastricht, green beaker base (MAJO= Jodenstraat, Maastricht).

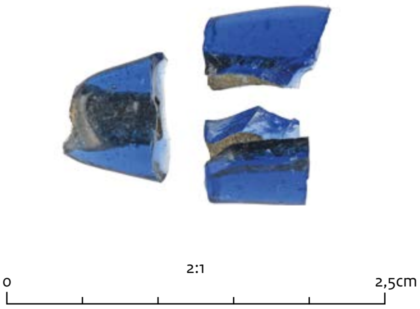


Figure appendix IV.36 Photo MAJO 25, Jodenstraat, Maastricht, blue punty glass (MAJO= Jodenstraat, Maastricht).

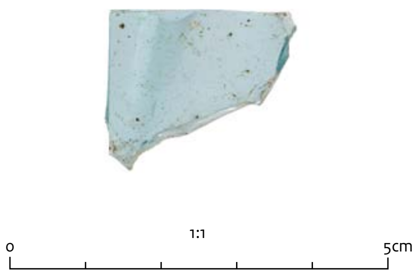


Figure appendix IV.37 Photo MAJO 26, Jodenstraat, Maastricht, blue-green flat ribbed fragment (MAJO= Jodenstraat, Maastricht).

Figure appendix IV.38 Photo MAJO 27, Jodenstraat, Maastricht, green glass rod fragments (MAJO= Jodenstraat, Maastricht).

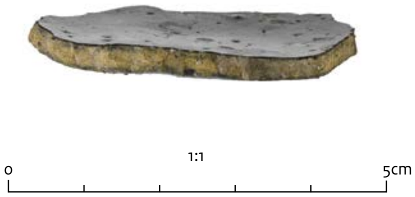


Figure appendix IV.39 Photo DOM 1, Domplein, Utrecht, Body fragment of crucible with colourless glass adhering (DOM=Domplein, Utrecht).

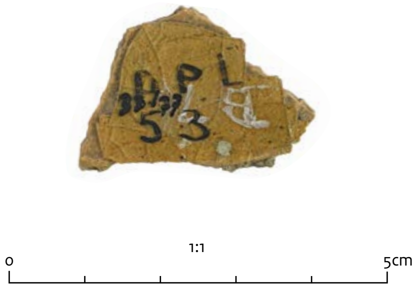


Figure appendix IV.40 Photo DOM 2, Domplein, Utrecht 2 Body fragment of crucible with colourless glass adhering (DOM=Domplein, Utrecht).

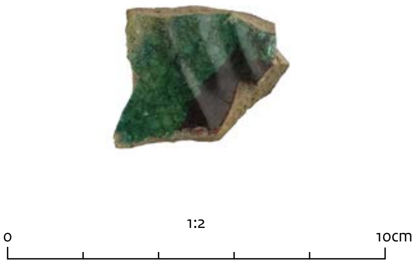


Figure appendix IV.41 Photo DOM 3, Domplein, Utrecht 3 Base fragment of crucible with pale green and red glass adhering (DOM=Domplein, Utrecht).

Figure appendix IV.42 Photo DOM 4, Domplein, Utrecht 4 Rim fragment of crucible with pale green and red glass adhering (DOM=Domplein, Utrecht).

Figure appendix IV.43 Photo DOM 5, Domplein, Utrecht 5 Rim fragment of crucible with green glass adhering (DOM=Domplein, Utrecht).

Figure appendix IV.44 Photo DOM 6, Domplein, Utrecht 6 Body fragment of crucible with pale green and red glass adhering (DOM=Domplein, Utrecht).

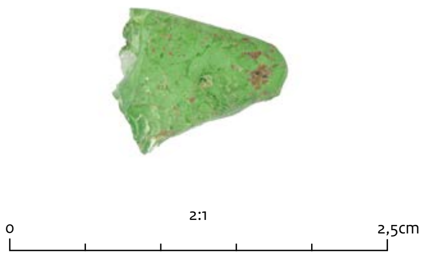


Figure appendix IV.45 Photo OUDWIJ 1 (sample 78), A lump of melted pale green glass from Utrecht (OUDWIJ=Oudwijkerdwarsstraat, Utrecht).

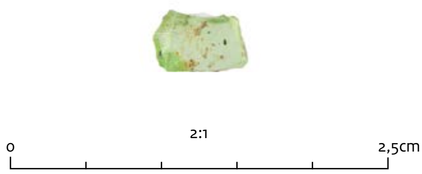


Figure appendix IV.46 Photo OUDWIJ 2 (sample 79), A chunk of pale green glass from Utrecht (OUDWIJ=Oudwijkerdwarsstraat, Utrecht).

This monograph brings together for the first time comprehensive combined archaeological, technological and scientific investigations of early medieval glass production in the Netherlands. The relationships between scientific results, archaeological contexts, sample dates, object types, colour, changes in glass technologies over time, as well as the social, economic and political factors affecting glass supply, and glass production, are discussed. We have selected samples from nine key sites, dating to between the late 4th and 11th centuries. Trace element and isotopic results for early medieval glasses have provided new and significant insights. They show that most glass in use was recycled and that there is a greater proportion of imported 'pristine' Egyptian glass in the Merovingian period than in the Carolingian period. A small proportion of wood ash glass was added to imported Carolingian glass found in the Netherlands; in contemporary northern Italian and Spanish glasses Levantine glass was added as part of the recycling process instead. We highlight the international importance of evidence for the production of yellow and white glass tin-based colorants in Maastricht and their use to make monochrome beads there. A wider range of glass technologies was in use after the 9th century following an important technological transition.

This scientific report is intended for archaeologists, as well as for other professionals and amateur enthusiasts involved in archaeology.

The Cultural Heritage Agency of the Netherlands provides knowledge and advice to give the future a past.