Dispersion of HIMT glass in Italy between the fourth and seventh century AD

Beek, Suzanne van

Dispersion of HIMT glass in Italy between the fourth and seventh century AD

Suzanne van Beek

Dispersion of HIMT glass in Italy between the fourth and seventh century AD

Suzanne van Beek, S1562460

2122-HS MA Thesis Global Archaeology, 1084VTGY_2122_HS

Prof. Dr. P.A.I.H. Degryse

University of Leiden, Faculty of Archaeology

Amsterdam, 7th of January 2022, Final Draft

Content

Acknowledgements

I would like to express my gratitude to my supervisor Prof. Degryse for the great support and patience during the writing of my thesis. Moreover, I want to thank Anna Hommel and René van Beek for proofreading the text and helping me through the process. Also, I am thankful for all my friends who helped with all the practical questions and struggles during the process of writing.

1. Introduction

Research on the chemical composition of antique glass has been increasingly executed on glass objects from the 1960s onwards. The gathered information can be used to compare and differentiate kinds of raw glass and their production places. Several different groups of raw glass could be distinguished based on their chemical composition.

Ancient glass consists of three main ingredients: sand (as a source for silica (SiO_2)), lime as a stabilizer, and a flux. The specific chemical composition of glass artefacts will be explained more elaborately in the second chapter. The sand used for glass production was never completely clean, so next to the three main ingredients iron was also present in the glass. This often led to an unintentional green or blue colour of the unworked, raw glass. From the fourth century AD onwards, a new type of raw glass was introduced, probably originating in Egypt (Nenna 2014, 177, 179). This glass was distinguishable by its yellow to olive green colour and was initially called HIMT (High Iron, Magnesium, and Titanium) glass. In 1994, the term HIMT glass was used for the first time in Freestone's publication of his analysis of raw glass found in Carthage (Nenna 2014, 177).

HIMT glass contained elevated levels of iron (Fe), manganese (Mn) and titanium (Ti), which were unusual for the glass that was made until the fourth century AD (Nenna 2014, 177). From the fourth until the seventh century AD, HIMT glass was widely dispersed in the Mediterranean area and beyond. Other glass groups were already distinguished and published earlier in academic reports by among others Nenna (*et al.* 1997 and 2000) who defined compositional types of glass originating in Egypt and Freestone (*et al*. 2000) who looked at compositional groups from the Levant (Henderson 2013, 95).

In a recent article, De Juan Ares *et al.* (2019) have published their findings on two subgroups of HIMT glass, HIMTa and HIMTb. These groups are dated to the fourth to fifth centuries AD and excavated throughout the Mediterranean area and North-Western Europe. Research has shown that these groups have different distribution patterns, probably as a result of different geopolitical developments. The writers of this article emphasize that a large-scale approach to the dispersion of HIMT glass and its supply patterns is needed to be able to explain the dispersion of the different kinds of glass objects. As suggested by De Juan Ares (email correspondence), the overview provided in his article could be completed with local studies, since he argues that the data for the Iberian Peninsula are complete. However, the data from several other countries, including Italy, have not been thoroughly researched yet. This is one of the reasons why the HIMT glass assemblages found on the Italian peninsula are the focus area in this thesis.

Moreover, glass, including the HIMT variant, is a material that has been found in large amounts during excavations in Italy. This provides many possibilities for comparative research within and outside the Italian peninsula, making Italy an interesting case study for the research on HIMT glass. Furthermore, Italy played a large role in the trade networks during the fourth to seventh centuries AD, which might provide explanations for the distribution of glass objects, including HIMT glass, throughout the peninsula. This thesis will assess the dispersion of HIMT glass throughout the Italian peninsula and link it with the broader distribution patterns of glass during this period. The main research question is: '*How is HIMT glass dispersed in Italy during the fourth to seventh centuries AD?*'

1.1 Research on glass

Research on the production process of glass has resulted in several discoveries. A distinction can be made between primary and secondary production phases of antique glass. Moreover, theories have been formed on local versus centralized production of antique glass (Freestone 2005, OO8.1.3; Paynter 2006, 1038). Primary production of glass is the first stage of glass production. The raw ingredients, sand and soda (natron), are mixed in furnaces and molten into blocks of glass. The secondary production stage is explained as the softening and shaping of chunks and blocks into actual objects.

Two theories have been developed concerning the actual process of glass production: local production versus centralized production. The local production theory explains that raw glass was produced at multiple places throughout the Roman empire. This theory is

Figure 1: Slab of glass at a primary production centre at Bet She'arim, Israel (https://www.cmog.org/).

contradicted by the centralized theory, which states that there were only a few primary production centres, primarily in Egypt and the Levant, where large chunks or slabs of raw glass were produced (fig. 1). After the production, these large chunks of raw glass (fig. 2) were shipped to many places throughout the Roman Empire where they were locally transformed into objects at secondary production centres (Degryse 2014, 20). The commonly used theory is the centralized theory, also in the research on HIMT glass. It is generally accepted that raw HIMT glass was produced in Egypt between the fourth and seventh century AD and traded in chunks throughout the Mediterranean area and North-Western Europe, where it was locally formed into vessels (Jackson and Foster 2015, 49; Nenna 2014, 179).

Figure 2: Reconstruction at the Israel Museum, Jerusalem of glass chunks ready for re-melting and blowing into vessels, stored in a ceramic vessel in the 6th-7th century workshop at Beth Sean, Isreal (Rehren & Freestone 2015, 237).

Current research on Roman glass is largely linked to research about the technological development of the material and social development concerning the use of the material. The way artefacts were produced and consumed can be used as an indicator of the transformation and complexity of a society (Jackson and Foster 2015, 44). This idea is also described by Fleming (1999), who writes that the development of the Roman Empire is being mirrored by the invention and adoption of glass production. By this idea, he indicates that the invention of glassblowing and widespread glass production shows the increasing complexity, cleverness, and structure of Roman society.

Over the years, research on glass has become very interdisciplinary and still increasingly combines several different research fields. However, this has not always been the case. Around the 1950s, the knowledge of the composition of ancient glass was mostly based on research from the late 18th century (Jackson and Foster 2015, 45). The social and technological explanations for the formation of those groups or the explanation for their dispersion was not yet considered during research.

During the 1950s and 1960s, several chemical analyses of ancient glass were published by Turner (1956), Geilmann (1955), Sayre (1961), and Brill (1969). These publications, mostly the research by Brill, have played an important part in the research on the chemical composition of glass. This was the start of the scientific analysis of glass (Rehren and Freestone 2015, 233). At the same time, glass research got more attention with the establishment of heritage studies of Roman glass in the 1950s. Glass was now also categorised by form, colour, and techniques, and its distribution was mapped and identified. This research approach continued in the 1960s. However, possible socio-cultural explanations for changes in glass production and dispersion were not yet linked to the scientific properties of the glass (Jackson and Foster 2015, 45-46).

After two decades, during the 1980s, improvement of the research methods took place. Theoretical scientific archaeology advanced significantly, which was also visible in the research field of glass. The chemical compositions of glass were combined with contextual and stylistic information. This resulted in information about the composition of Roman glass through the ages and that it was not as homogeneous as initially thought. The differences in composition were explained by a probable use of different sources for the raw material. This was the first step towards understanding the way in which the Roman glass industry was organised (Jackson and Foster 2015, 46-47).

During the 1990s, the study of the chemical composition of glass became an interdisciplinary field of research and needed a more systematic and refined methodology. The main research problems that were encountered were the identification of primary and secondary production sites and the recycling of ancient glass. Another focus area was colourless glass. Colourless glass was thought to have had a higher value in antiquity and therefore also more sensitive to trends, which should have made it easier to place these objects into a context and chronology. However, within this group of colourless glass, subtle compositional differences could be distinguished, indicating that differences within groups of glass were not only caused by style but rather by the organisation of the different production places of glass (Jackson and Foster 2015, 47). During this period, researchers figured out how to discover the date and provenance of glass samples with information from chemical analysis. By re-examining the chemical composition of glass and comparing these differences with each other, new compositional data were discovered and more information about the organisation of production was constructed (Jackson and Foster 2015, 48).

In the last couple of decades, research on ancient glass has gotten the attention of a wider group of scholars, which resulted in new approaches in the research and growing research activity. Rehren and Freestone (2015, 233) give three main reasons for this development, which include "*the rapid development of new analytical techniques requiring ever smaller sample volumes; the increasing archaeological interest and excavations targeting more technical sites; and the development of interpretative models based on the series of analyses in a wider theoretical concept."* Next to these three factors, research has also been focused on the comparison of local site assemblages to a larger regional corpus of known glass forms, which can provide a more nuanced understanding of glass production and use. Furthermore, glass recycling is also a topic that has received more attention (Keller *et al.* 2014, 4). An elaboration on this topic can also be found in the second chapter. In the research on HIMT glass, glass recycling is an important aspect since indications of this particular production process are found in HIMT artefacts. Moreover, research has shown that even glass coming directly from the primary production sites is not homogeneous, which means that from batch to batch differences in chemical composition can be seen. These differences can be increased or decreased by the recycling of old glass (Rehren and Freestone 2015, 239).

Because of the constant development of new research methods, the use of chemical analysis on glass objects is still increasing and being improved. This results in a growing number of glass objects which have been subjected to chemical analysis. The already acquired corpus of data is being expanded, which makes it possible to compare the chemical composition of different kinds of glass to distinguish them and identify their provenance (Nenna 2014, 179-180).

1.2 Study in HIMT glass

During the mid-1990s, several researchers including Freestone (1994), Mirti *et al.* (1993), and Verità (1995) distinguished a new kind of glass, HIMT glass, unique for its high iron (Fe), manganese (Mn), and titanium (Ti) levels. Even though it was recognized as a specific kind of glass, it was not yet assigned to a specific production place (Nenna 2014, 177). In the following decade, an increasing amount of chemical research on several kinds of glass from different geographical areas was executed. Based on this research on chemical composition, French and English researchers concluded independently that

HIMT glass originated in Egypt. This was based on the high level of titanium (Ti) (between 0.16-0.63%), which was characteristic for primary glass fabricated in Egypt. Glass originating in the Syria-Palestinian area always contains less than 0.10% titanium (Ti). Another addition was made by Freestone (Freestone *et al.* 2005), who said that a high soda content, as seen in HIMT glass, was also characteristic of Egyptian natron sources. Later on, the theory of Egypt as the primary production place for HIMT glass was strengthened by increased research on the isotopic composition of neodymium (Nd), which indicated the use of sand from Nile-dominated sediments, which is also explained more elaborately in the second chapter (Degryse and Schneider 2008, 1995).

In the last couple of years, research has started linking glass forms with the different compositions of glass. Foster and Jackson (2009) have shown in their research that, in general, HIMT glass may have been cheaper and therefore used for more utilitarian purposes. This is probably because the quality (of the technology) of the glass was lower than that of other glass compositional groups. The quality was also more variable and less expensive than other types of glass. Moreover, HIMT glass producers used glass that was already recycled in the primary production, without paying much attention to the consistency of the colour, therefore lowering the quality of the glass (Nenna 2014, 186). Other glass compositions, which are discussed in depth in the second chapter, for example, the Levantine I glass group originating in the Levantine coast, were produced with purer glass which appears to have been used for higher status vessels (Keller *et al.* 2014, 3).

1.3 HIMT glass in Italy

HIMT glass was widespread across the Mediterranean and North-Western Europe. Some of these areas have been researched already, like the HIMT assemblages from Spain (De Juan Ares), Great Britain (Freestone; Jackson and Foster), and France (Foy). Even though the HIMT glass assemblages found in Italy have not been researched as extensively as the ones described above, there is a growing number of publications on the presence of HIMT glass in Italy. Based on the existing literature on HIMT glass in Italy, 17 sites have been considered for this thesis. These sites all contain HIMT glass but the nature of the sites varies. In this thesis, a distinction has been made between consumption and production sites. The consumption sites are characterized by the fact that the glass was solely used at these places. Production sites, on the contrary, show signs of the manufacturing of glass artefacts, and sometimes also the use of these objects. It is interesting to compare these sites, to see if the glass assemblage from a production site differs significantly from a consumption site.

Most of the HIMT glass has been found in northern Italy, mainly in Aquileia and Classe, which are two known secondary glass production centres. Moreover, they were both important ports in antiquity (Bowersock *et al.* 1999, 307, 662). This can be an explanation for the large quantity of (HIMT) glass; these cities were part of a large trade system. HIMT glass has also been found in the rest of the Italian peninsula but to a lesser extent.

1.4 Research questions and methodology

To answer the main research question: '*How is HIMT glass dispersed in Italy during the fourth to seventh centuries AD?*', several sub-questions have been defined:

- *What does the chemical composition of ancient glass dating between the fourth to seventh century AD look like? How do we recognize the several glass groups including HIMT glass?*
- *How can we distinguish glass assemblages originating from either consumption or production sites?*
- *How can we explain the role of secondary production centres in the trade network?*
- *How can we explain the differences in composition of the glass assemblages and the amount of HIMT glass per site?*
- *What role does recycling play in the life cycle of HIMT glass?*

In the second chapter, information is provided about the basics of the chemical composition of glass and the distinction between the different glass compositional groups. Furthermore, this chapter also explains what HIMT glass comprises on a chemical level; how it distinguishes itself from other chemical glass groups; how it can be seen in glass assemblages; and where it has been found. The third chapter contains a description of the analysed sites. In the discussion, the information from chapter three is combined with cultural and geopolitical information, to reconstruct the life cycle of HIMT glass.

This research uses data based on publications of several glass assemblages from Italy containing HIMT glass. The data from these publications are linked to general information about trade routes in the discussion which shows how HIMT glass was dispersed in Italy.

2. Description of HIMT glass

This chapter will discuss the characteristics of HIMT glass and how we can recognize this particular kind of glass. To place this information in context, the first part of the chapter will give a basic overview of the chemical composition of glass and the several chemically different glass groups. Since HIMT is a glass group that is chemically distinct from several other glass groups, it is important to see what other glass groups have been distinguished to give a short overview of the glass market of which HIMT glass was part. The chapter will be concluded with the description of the several subgroups of HIMT glass.

2.1 Chemical composition

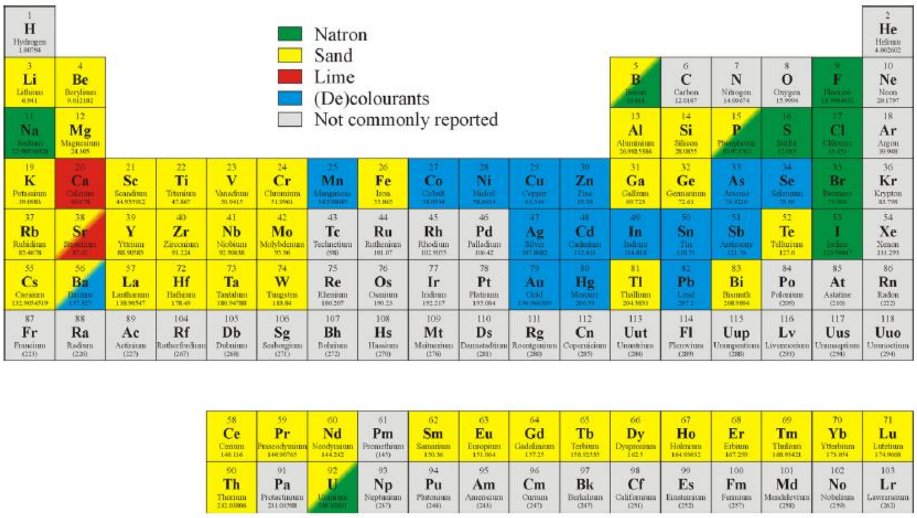

Figure 3: Indication of the most likely sources for elements present in natron glass after Brems and Degryse (2014, 118).

2.1.1 Basic ingredients of glass

Ancient raw glass is comprised of three main ingredients: sand (as a source of silica (SiO_2)), lime used as a stabilizer, and a flux. Silica (SiO_2) has a very high melting point, around 1700°C, which ancient furnaces could not reach. Therefore, a flux was added to lower the melting temperature of the raw material (Devulder and Degryse 2014, 87). In ancient glassmaking, there were two common fluxes: natron[1] (also known as *natrun*) or plant ash. Normally, these fluxes were not used together for the production of a

[1] "Evaporitic deposits containing sodium carbonate and sodium bicarbonate which have been exploited as a source of alkali for millennia. Natron is the mineral name for the sodium carbonate 10-hydrate, whereas the dominant carbonate in these deposits is frequently the sodium carbonate bicarbonate 2-hydrate, trona." (Shortland *et al.* 2006, 521).

single batch of raw glass. Chemical analysis has shown that between the second half of the first millennium BC and the ninth century AD, natron was used as the main flux in glass production in the Mediterranean region (Degryse and Shortland 2020, 3). According to several ancient authors, there were several sources for natron (fig. 4). Strabo and Pliny the Elder (Pliny NH 31.46; Strabo Geography 17.1.23) both mention areas in Egypt, like the Wadi Natrun and Al-Barnuj, the regions around Naucratis, and Memphis. Besides these regions, there are more possible natural sources. For example, Pliny refers in his writings also to Lake Pikromini, located in Macedonia. Lake Van (Armenia) and Lake Jabbul (Syria) might have been possible natural sources as well (Shortland *et al.* 2006, 576) (fig. 4). Devulder *et al*. (2014, 108) add also at-Tarabiya in the Eastern Nile delta, al-Kab in upper Egypt or Bi'r Natrun on the route to Darfur in Sudan.

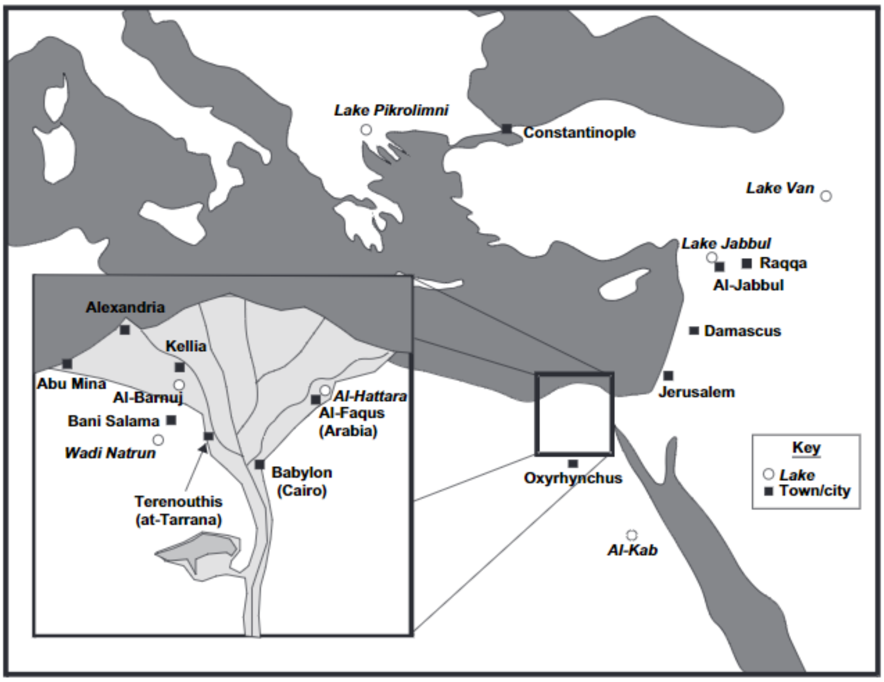

Figure 4: Natural natron sources (Shortland et al. 2006, 576).

In the periods before the second half of the first millennium BC and after the ninth century AD, plant ash was most often used as a flux. However, even between the second half of the first millennium BC and the ninth century AD, plant ash glass is still used to a lesser extent besides natron glass in the Far East (Degryse and Shortland 2020, 3). Plant ash fluxes were retrieved from the ash of coastal and desert plants. The glass made with plant ash flux is characterized by the presence of elevated levels of potassium (K) and magnesium (Mg) higher than 1.5%, and phosphorus (P) up to 1%, while natron glass does not have these higher levels (Degryse and Shortland 2020, 2-3). Since this thesis is focused on fourth to seventh century AD glass in the Mediterranean area, natron is the most commonly used flux in the glass assemblages.

As stated above, a flux brings down the melting temperature by weakening the chemical bonds between the elements (Fiori and Vandini 2004, 152). However, a flux destabilizes the chemical bond to such an extent that stabilizing ingredients have to be added, like lime and/or magnesia. Otherwise, the glass, only consisting of silica (SiO_2) and a flux, would be unstable and easily damaged upon contact with water (Scott and Degryse 2014, 20). In natron glass, lime is added to the mixture as particles of shell or limestone. This could have happened either unintentionally when lime naturally occurs in the silica source and is added to the mixture together with the silica, or by adding it intentionally during the production process (Degryse and Shortland 2020, 3). However, ancient texts written about the production of glass only mention two raw materials, sand and flux, which indicates that the stabilizing elements must have occurred naturally in the silica source (Degryse and Shortland 2020, 4; Fiori and Vandini 2004, 152).

2.1.2 Colouring

Next to the silica, flux and lime, more elements were intentionally or unintentionally added to the mixture. An example of an unintentionally added element is iron (Fe), which always came along with the sand and caused a green-blue tint (Bugoi *et al.* 2018, 574). Therefore, glass objects which were not deliberately decoloured or coloured had a bluish green colour.

Elements are considered as deliberately added when they occur in a concentration higher than 1000 parts per million (ppm) and were added with the intention to alter the chemical composition of the glass (Brems and Degryse 2014, 73). Several different metals were used to colour, decolour or opacify the glass. The most common elements which are associated with (de)colouring or opacifying in ancient glass are, among others, cobalt (Co) for deep blue, manganese (Mn) for decolouring and purple, copper (Cu) for blue, blue/green or red, antimony (Sb) for decolouring or opacifying, tin (Sn) for an opaque white colour and lead (Pb) in combination with antimony (Sb) or tin (Sn) to create opacified yellow glass (Degryse and Shortland 2020, 7). The final colour was not only depending on the kind of metal that was added to the glass, but also on the reducing or oxidizing state of the furnace. This means that the colour of the glass could differ depending on the level of oxygen in the furnace. Furthermore, the temperature, the timing of the melting point, the type of glass matrix, and the presence of one or more chromophoric[2] elements in the mixture could also make a difference in the colour of the final product (Degryse and Brems 2013, 5).

Manganese (Mn) and antimony (Sb), could function both as a colourant and as a decolouring agent, depending on the level of oxygen present in the furnaces. However, the amount of an element present in the matrix is also important for the colouring result. For example, a manganese (Mn) content always over 1% might be an indication for the intentionally added element to counteract the iron in the raw mixture to prevent the glass from turning green (Cagno et al. 2012, 1544). Research showed that a higher amount of manganese (Mn) is needed to create the same level of decolouration compared to when antimony (Sb) is used (Bugoi *et al.* 2018, 574-575). Before the late first century BC, glass was mainly decoloured with antimony (Sb). However, around the fourth century AD, antimony (Sb) was replaced by manganese (Mn) as a decolourizer (Degryse and Shortland 2020, 8).

2.1.3 Recycling

Glass recycling is seen as the use of glass fragments of already formed objects in the process of making raw glass (Duckworth 2020, 306). The clearest indicator of recycling on an archaeological site is the presence of cullet. This is generally found on workshop sites as dumps, on domestic or storage sites, and on some shipwrecks (Duckworth 2020, 311).

For the recognition of recycled glass, there are five markers that are usually considered: the presence of the colourants copper (Cu), cobalt (Co) and/or lead (Pb), the presence of antimony (Sb) and manganese (Mn) together, and the presence of both plant ash and natron glasses (Duckworth 2020, 332).

Recycling is indicated by concentrations of elements higher than natural occurring elements, but lower than intentionally added elements (Degryse and Brems 2014, 5). The elements manganese (Mn) and antimony (Sb) can also be used as indicators for

[2] A group of atoms and electrons forming part of an organic molecule that causes it to be coloured (https://www.britannica.com/).

recycling. Initially, they were used separately to decolour the glass. This means there was either manganese (Mn) decoloured glass, or antimony (Sb) decoloured glass. However, when these elements are found together in colourless glass, this might be because old glass scraps were mixed together to make a new batch of raw glass. Other elements that can indicate recycling are copper (Cu), but also lead (Pb), for this might point to the incorporation of old coloured and opaque glass into a new mixed batch (Bugoi *et al.* 2018, 575; Degryse and Shortland 2020, 9).

Another indication of recycling is the presence of a heightened level of potassium (K_2O) and magnesium oxide (MgO), as this could signify a mixture of natron and plant ash glass. As mentioned earlier, these two fluxes were normally not used together. When they are found together in one glass, it could indicate the mixture of two different batches of glass to create a new one (Bugoi *et al.* 2018, 577). The use of these elements as indicator for recycling is, however, debated since the co-occurrence of these elements in non-recycled glass is also possible. Plant ashes were also added as part of the colourant to some coloured Roman glass (Paynter and Jackson 2016, 40).

Glass recycling in antiquity occurred as the addition of glass cullet (fragments of broken objects) to 'fresh' glass, after which it is melted into a new batch of glass. The option of a whole batch of melted glass artefacts is also possible, however, the use of too much cullet influences the viscosity of the glass mix and can hinder the process of glass blowing. By using scrap glass in the glassmaking process, the melting temperature of the glass mixture decreases which results in lesser use of fuel and the reuse of secondary raw material (Degryse 2020, 287). Next to improving the fusion of the raw ingredients and forming new glass, cullet was also very efficient for the input of volume during the making of new glass. By using only raw material, a lot of waste gases, burning of organic material and evaporating water will result in a lower amount of glass, while with the addition of glass cullet, only the air between the glass fragments will be 'lost space'. Therefore, these recycling practices might have already been incorporated in the primary production of glasses (Duckworth 2020, 306). This type of recycling is the hardest one to detect, because in contrast to what is often believed, similar kinds of glass were probably used to recycle, instead of using fully different compositional groups. That also makes sense because higher quality, colourless glass would preferably not be mixed with lower quality glass, as that would degrade the value of the glass. Recycling with two different chemical compositional groups is easier to discover, because, for example, two different decolouring agents can be traced in the mixture (Duckworth 2020, 304, 318)

Experimental research by Scott (*et al.* 2017) shows that natron glass can be recycled at lower temperatures than plant ash glass. Therefore, only later in the development of glass making, when higher temperatures could be reached by the glass making furnaces, the use of recycling practices increased (Degryse 2020, 289). There is, however, a limit on how often glass can be recycled. Every time the glass is recycled, the material degrades a little because of the pollution of the furnace environment and glassmaking tools and the loss of fluxes (Freestone 2015, 30). In combination with the influence of cullet on the viscosity, blown glass was probably not the most recycled glass, but highly coloured, non-blown objects were. They are least influenced by the 'degradation' of the raw glass mixture by the recycling practices. Therefore, the focus as it is now, on vessel glass, should shift to include other kinds of glass which are more likely to contain recycled glass. Moreover, this should also show the total volume of recycled glass instead of recycled glass within only one group (Duckworth 2020, 338-339).

The exact amount of recycled glass is still debated. Degryse (2020, 294) states that at least a quarter, but probably more, of the glass is recycled, while Duckworth (2020, 345) suggests that over 50 percent of the glass shows signs of recycling.

2.1.4 Chemical composition, isotopes, and provenance

The main theory about the provenance of glass is that raw glass was made in batches at a few primary production centres in Egypt and the Levantine area, after which it was shipped in blocks throughout the Mediterranean area and North-Western Europe (De Juan Ares *et al.* 2019, 1; Nenna 2014, 1). The location of the primary production centres depended on several factors. Since sand was one of the main ingredients of ancient glass, it was important that sand sources were easily accessible. As mentioned in the introduction, several main sand sources were exploited during ancient glass production. However, not all sand was suitable for glassmaking. In ancient texts, written by among others Pliny the Elder and Strabo, the main sand sources described are the Belus delta in current Israel and the Wadi El Natrun region in Egypt. Pliny also mentions the Volturno river in Italy as a source for sand suitable for glass making. However, research has proven that the sand from the Volturno river is not suitable for glass production (Brems and Degryse 2014, 27-28; Fiori and Vandini 2004, 154, 177). Another factor which needed to be considered for the establishment of a production centre is the proximity of fuel sources like wood. The furnaces needed a lot of fuel to heat the glass mixture to the melting temperature.

Natron glass, which also includes HIMT glass, has a very uniform elemental composition. This means that all the glass fabricated with natron as a flux contains similar ingredients with similar levels, which makes it more difficult to distinguish the different kinds of natron glass. Therefore, when researching the origin of the sand source, besides the major elements found in glass composition, trace elements and radiogenic isotopes (expressed in ratios) are considered as well. Trace elements are measured in parts per million (ppm), which indicates the number of units of mass of an element per million units of total mass. Isotopic research is particularly useful, since isotopic values in the glass matrix are barely changed by transformations like melting. Therefore, for example strontium (Sr) and neodymium (Nd) and other isotopes are very useful to discover provenance information of the raw materials used for glass production. The isotopic signature of the artefact is dependent on the geological age and the provenance of the raw material (Gallo *et al.* 2015, 55-56).

One of the isotopes which is used for origin research is strontium (Sr). Strontium (Sr) shows *'(1) the mineralogy age, and crustal versus mantle source for igneous and metamorphic rocks; (2) the provenance and maturity for sandstones and shales; and (3) the age and extent of alteration for marine carbonates, evaporites and phosphorites*' (Brems *et al.* 2014, 52). The strontium (Sr) content is a good indicator of the source of lime, since lime could be retrieved from coastal (seashell) or inland (limestone) sources. Seashell contains a few thousand strontium (Sr) ppm, while limestone will only contain a few hundred strontium (Sr) ppm. Therefore, natron glass which contains limestone will have less than 200 ppm strontium (Sr), but when shell fragments are used as lime source, the glass can contain 300 to 600 ppm strontium (Sr) (Brems *et al.* 2014, 53). The provenance of strontium (Sr) can also be determined with the $^{87}Sr/^{86}Sr$ isotopic ratio. This ratio reflects the natural occurring level of strontium (Sr) in the soil and therefore is indicative for the geological origin of the soil (Brems *et al*. 2014, 58). The $^{87}Sr/^{86}Sr$ isotopic ratio of shells lies around 0.7092 and is similar to the $^{87}Sr/^{86}Sr$ isotopic ratio of present-day seawater. The ratio of limestone can vary between 0.707 and 0.709 (Brems *et al.* 2014, 58). HIMT glass seems to have an Sr ratio between 0.7075 and

0.7090 (Degryse *et al.* 2014, 104). Not only limestone introduces strontium (Sr) into the glassmaking mix, but magnesium (Mg), iron (Fe), titanium (Ti) bearing minerals, like pyroxenes and amphiboles, can also introduce this isotope (Maltoni 2016, 14). These minerals are generally found in more impure coastal sand or inland sediments, and were often seen in Nile Delta sand (Maltoni *et al.* 2016, 12). This can also be an indication for the use of lime from these Nile Delta sands in the production of HIMT glass.

Even though it can be concluded from these strontium (Sr) contents whether the lime, and therefore the sand source, comes from a coastal area or a source further inland, it cannot give complete certainty, because there are also lime sources that are located in coastal regions and not only in the inland regions (Degryse *et al.* 2014, 230).

Another isotope which is considered in isotopic research is neodymium (Nd). In Roman natron glass, the neodymium (Nd) isotopes come from the non-quartz minerals in the mixture for raw glass and can yield information about the age of the sediments (Degryse *et al.* 2014, 230). Neodymium (Nd) signatures in glass objects lie, in general, between -12.0 ε_{Nd}[3] and -1.0 ε_{Nd} (fig. 5). Glass from the western part of the Mediterranean has a low neodymium (Nd) signature ranging between -12.0 and -7.0 ε_{Nd}. Glass from the

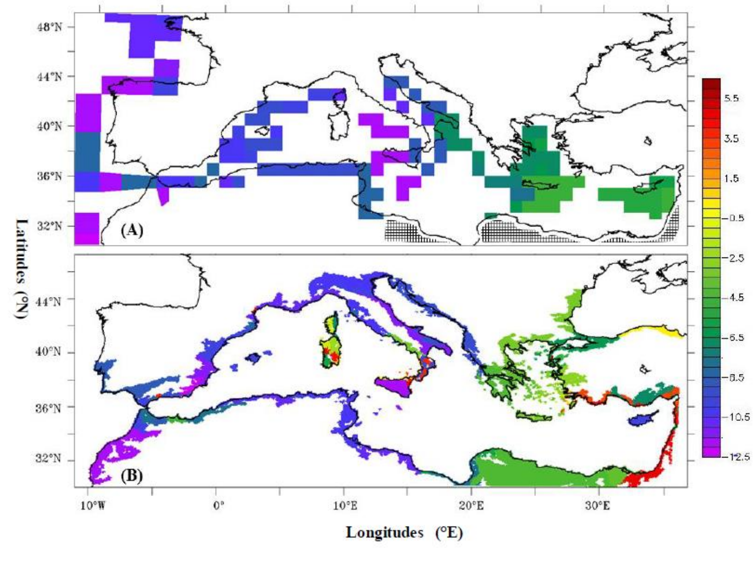

*Figure 5: The levels of Neodymium (Nd) along the Mediterranean coast (*Brems *et al.* 2014, 54).

Eastern Mediterranean area, like from Bet Eli'ezer and Apollonia in Israel (fig. 8) dating between the sixth and the eight century AD, has an isotopic signature between -4.1 and -5.1 ε_{nd}. Sand on the Eastern Mediterranean coast derives partly from the Nile, because

[3] "A standardized notation comparing the measured value to an internationally recognized standard value." (Degryse *et al.* 2014, 332).

the currents move the sand from the Nile delta all the way up to the Israelian coast. Nile sediments contain minerals from young volcanic rocks in East Africa. Therefore, East Mediterranean sands have high ε_{nd} values, up to -1 ε_{nd} at the mouth of the river Nile (Brems *et al.* 2014, 54). HIMT glass can be distinguished by the fact that it has an isotopic signature between -4.0 and -6.0 ε_{Nd} (Degryse *et al.* 2014, 332), which means that Nile sediments fall in the range of the neodymium (Nd) signatures of HIMT glass, and might also indicate the production of HIMT glass with sand from the Nile.

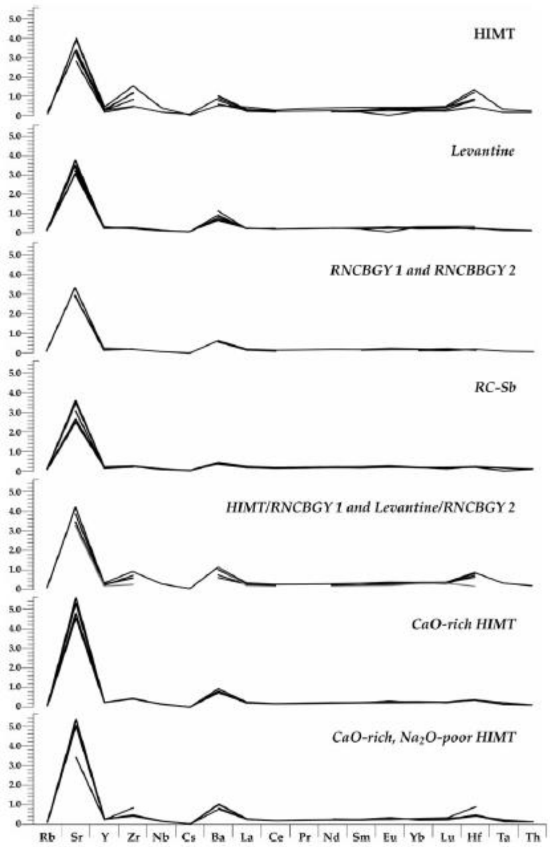

Figure 6: Trace elements/REE patterns per glass group (Gliozzo et al. 2016, 95).

Next to the isotopes and elements described above, there are also several trace elements which can be used for provenance research to distinguish different glass compositional groups (fig. 6). The trace elements which are mostly used in the publications considered for this thesis are zirconium (Zr), hafnium (Hf), barium (Ba), chromium (Cr), vanadium (V), nickel (Ni), and the REE (Rare Earth Elements; lanthanum (La) to lutetium (Lu)). The REE can also indicate different sand sources by considering geological traits in the sand and the environment. REE compositions are '*normalized to the Earth's continental crust composition and described as enriched or depleted compared with the average crust*'. These elements are mostly found in the silt and clay parts of the raw mixture of glass, and they are not subject to change by the production process of glass. The only way REE patterns can differ is when they originate from different geological environments (Degryse and Shortland 2020, 6). Recent research on one of these trace elements, hafnium (Hf), has shown that a more clear distinction between Levantine and Egyptian glass can be made based on the isotopic ratio of this element in the raw glass. Strontium (Sr) and neodymium (Nd) often have overlapping ratios for both areas, because the Nile sediments, from which their ratios are deducted, are spread along both the Egyptian and the Levantine coast. Hafnium comes from the mineral zircon, which traces the quartz component in the weathered and eroded rests of rock formations. Research has indicated that the level of zircon (Zr) drops during the transport of sediments along the shore, resulting in hafnium (Hf) concentrations of 2-4 ppm in Egyptian glass and 2 ppm or lower hafnium (Hf) concentrations in Levantine glass (Barfod 2020, 5). By looking at the chemical composition and the isotopic signature of the glass, several groups of chemically distinct glass compositions can be identified. The glass groups dating between the fourth and the ninth centuries AD are described below.

Group		Roman imperial age	HIMT	CaO rich HIMT	Groupe 1	Groupe 2	Série 2.1	Série 3.2	RNCBGY 1	RNCBGY 2	Sb-decoulorized	Mn-Decolourized	Sb+Mn Decolourized	Levantine
Source		Arletti *et al*. 2010, 260	Gliozzo *et*	Gliozzo *et al*. 201	Foy *et al.*	Foy *et al.*	Foy *et al.*	Foy *et al.*	Gliozzo *et al.*	Gliozzo *et a*	Maltoni *et al.* 2016	Maltoni *et al.* 2016,	Maltoni *et al.* 2016, 7	Gliozzo *et al.*
N		8	396	81	43	61	51	19	290	77	7	10	6	152
SiO2	a	71,1	67,8	66,1	64,49	64,67	64,42	69,07	69,8	70,6	70,75	69,39	69,94	69,9
	s	0,9	2,1	0,6	1,36	1,37	1,05	1,49	0,9	1,4	2,01	0,6	0,51	1,8
Al2O3	a	2,41	2,4	2,4	2,88	2,53	2,54	1,92	2,4	2,5	2,14	2,67	2,26	2,9
	s	0,13	0,3	0,3	0,26	0,15	0,15	0,15	0,2	0,2	0,39	0,19	0,11	0,2
TiO2	a	0,06	0,24	0,5	0,49	0,16	0,16	0,09	0,1	0,1	0,08	0,07	0,08	0,08
	s	0,006	0,16	0,05	0,12	0,02	0,02	0,02	0	0	0,03	0,01	0,01	0,02
CaO	a	6,43	6	8,2	6,22	7,73	7,78	6,99	6,7	7,7	5,93	8,09	6,75	8,7
	s	0,67	0,6	0,5	0,85	0,63	0,67	0,74	0,5	0,5	1,15	0,45	0,31	0,9
MgO	a	0,76	0,9	1	1,23	1,2	1,23	0,65	0,6	0,5	0,49	0,53	0,54	0,6
	s	0,41	0,2	0,2	0,24	0,18	0,15	0,16	0,1	0,1	0,17	0,09	0,04	0,1
Na2O	a	18,18	19,4	17,7	19,12	18,37	18,5	18,79	17,5	16,1	18,06	15,46	17,33	15,6
	s	1,41	1,1	1	1,34	1,24	1,22	0,85	0,7	0,9	1,03	0,45	0,54	1,2
K2O	a	0,44	0,5	0,7	0,41	0,79	0,79	0,44	0,7	0,8	0,39	0,55	0,59	0,8
	s	0,07	0,1	0,1	0,08	0,14	0,14	0,08	0,2	0,3	0,08	0,11	0,07	0,2
Fe2O3	a	0,38	1,1	1	2,28	1,32	1,35	0,7	0,5	0,4	0,46	0,42	0,49	0,4
	s	0,05	0,6	0,3	0,86	0,62	0,65	0,15	0,1	0,2	0,17	0,06	0,05	0,1
MnO	a	0,635	0,3	1,4	2,023	1,503	1,601	0,953	0,4	0,5	0,02	1,49	0,6	0,6
	s	0,557	0,5	0,3	0,398	0,504	0,369	0,338	0,2	0,4	0,01	0,32	0,12	0,6

Figure 7: Values per compositional group in wt%. Based on Arletti et al. 2010, Gliozzo et al. 2016, Gliozzo et al. 2017, Foy et al. 2003, and Maltoni et al. 2016.

2.2 The different kinds of glass groups

In this chapter several different kinds of glass groups are described. These particular glass groups are being considered because they are either found together with HIMT glass, or produced during the same period of time as HIMT glass was produced.

2.2.1 Egypt I and II

The terminology of these glass groups was introduced a couple of decades ago by Gratuze and Barrandon (1990). Since then, chemical research on glass has been evaluated, resulting in the discovery of new groups and already specified groups that are being revised. For example, the terms Egypt I and Egypt II are often discussed, since other differentiations have been made between the different glass groups from Egypt as well. However, since the terms have been used and are still being used in the publications of the glass assemblages that contain HIMT glass and are used for this thesis, these terms are also used in this thesis.

Egypt I is one of the major glass groups which was produced in Egypt. The introduction date is unclear, but glasses from this type seem to have been used during the seventh to the eight century AD. These glasses are known for its high magnesia (Mg) (0.92-1.35 wt%[4]) and low lime (CaO) (2.6-4.5 wt%) concentration. Egypt I has, similar to Egypt II, an alumina (Al_2O_3) content higher than 2 wt% and a titanium oxide (TiO_2) content higher than 0.25 wt%. This glass type is already scarce in Egypt and also very rare outside of Egypt. The western Nile Delta nor the North Sinai area yield glasses of the Egypt I group dating to the period before the seventh and eighth centuries AD (Ceglia *et al.* 2015, 219; Degryse *et al.* 2014, 104, 107). Egypt I corresponds with Egypt IA and Egypt IB, which are glass groups that are determined by Schibille *et al.* (2019). Schibille *et al.* (2019) have executed new research on Egyptian glass compositions since, until recently, the Egyptian compositional glass groups have been based on research done circa 30 years ago. Egypt IA and IB are characterised by their similar levels of lime (CaO) and natrium oxide (Na_2O). Egypt IB differs from Egypt IA due to its lower levels of alumina (Al_2O_3), magnesia (MgO), titanium oxide (TiO_2) and zirconium (ZrO_2). Also the trace elements from both Egypt IA and Egypt IB show similar overall patterns, except for that Egypt IA has on average a factor of 1.5 lower (Schibille *et al*. 2019, 12). In terms of dating, going from Egypt 1A to Egypt 1B occurred between 720 and 725 AD. Before 720, Egypt 1A

[4] Weight percentage.

dominated the glass assemblages, and afterwards Egypt 1B took over and lasted until 780 AD (Schibille *et al.* 2019, 14, 17).

Egypt II is another chemically distinct glass group produced in Egypt. Gratuze and Barrandon (1990) were the first researchers to identify this type of glass. Egypt II glass is known for its high lime content, calcium oxide (CaO) around 9%, and the low alumina (Al_2O_3) content around 1.5-2.5%. Further isotopic research on the strontium (Sr) isotopes indicates that the glass was made with inland sand. This is concluded because results from strontium (Sr) research prove that the lime content in the sand came from limestone rather than from seashells. Egypt II glass was predominant in the eighth and ninth centuries AD and characteristic for the glass workshop in Tell el Ashmunein located in Middle Egypt and glasses from Ramla in Israel (Fiori and Vantini 2004, 166; Freestone *et al.* 2000, 73). Egypt II glasses have rarely been found outside Egypt itself (Degryse *et al.* 2014, 107). Egypt II shows similarities to Egypt 2 from Schibille *et al.* (2019). Schibille *et al.* (2019, 12) write about similar high levels of calcium oxide (CaO) with low alumina (Al_2O_3) and strontium (Sr). Egypt 2 shows in general lower trace and rare earth elements (REE) apart from zirconium (Zr) and hafnium (Hf). It is stated that Egypt 2 is the last natron-type glass produced in Egypt. It was mostly used from 780 AD until 870 AD (Schibille *et al.* 2019, 15, 17).

In general, even before the introduction of Egypt I and Egypt II glass, Egyptian glass has a higher level of silica-related heavy element impurities. Also the use of antimony (Sb) to decolour the glass is one of the main characteristics of Egyptian glass production until the fourth century AD (Juan Ares *et al.* 2019, 23-24).

2.2.2 Levantine glass

The other main area for glass production is the eastern Levantine coast, the coast of current day Israel. Levantine glass is known for its blue-green colour and its more viscous, high working temperature (Freestone *et al.* 2014, 159). In Levantine glass production, a division is being made between Levantine I and Levantine II glasses. Both Levantine glass groups have a strontium (Sr) ratio close to 0.7092, which is the strontium (Sr) ratio of Holocene seawater. This implies the use of beach sand as raw material (Freestone *et al.* 2018, 173).

Levantine I glasses are dated to the period between the fourth and seventh centuries AD and are known as Roman-Byzantine glass. Three main production areas have been distinguished. Two of them are located in Israel, at the sites Dor and Apollonia, where the glass production from the Byzantine period (sixth-seventh century) took place. Jalame, a site in Palestine, yielded a glass production centre dating to the late Roman period (fourth century) (Fiori and Vantini 2004, 166; Freestone *et al.* 2000, 72).

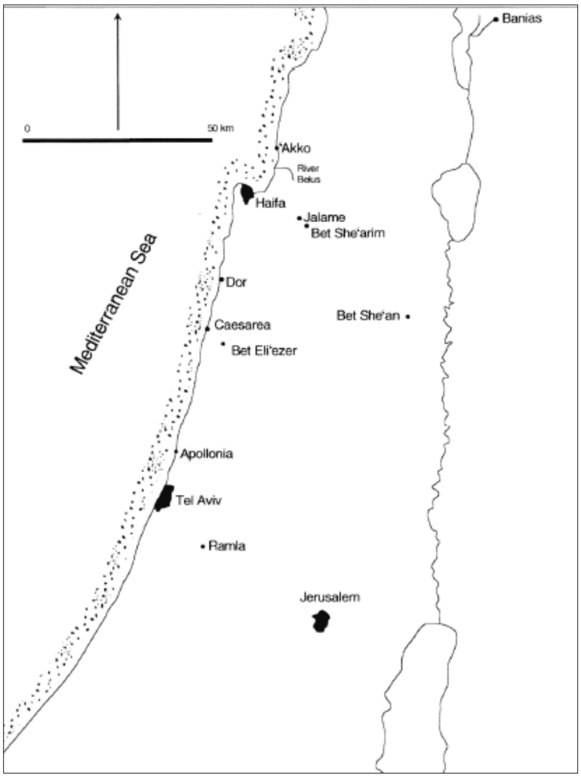

Figure 8: Important sites and glassmaking sites on the Palestinian coast (Freestone et al. 2000, 68).

The glasses were produced with coastal sand from the Haifa bay, close to the Belus delta, which can be concluded from the presence of seashell parts functioning as lime stabilizer. Natron served as the soda flux. The lime content (CaO) in Levantine I glass lies around 8-9% and the alumina (Al_2O_3) content fluctuates between 2.5-3% (Freestone *et al* 2000, 73).

Levantine I glass is dispersed throughout the Roman empire, but its presence in glass assemblages becomes increasingly smaller the further it spreads from the production place. Levantine I is often found in similar contexts as HIMT glass (Fiori and Vantini 2004, 167).

Levantine II objects were produced between the sixth and seventh centuries AD in Israel at the site Bet Eli'ezer. It is known as Late Byzantine – Umayyad glass (Henderson 2013, 242). It can be separated from Levantine I glass by its lower soda and lime (CaO) content and higher silica (SiO_2) and alumina (Al_2O_3) percentages. This can be explained by the use of different ratios between sand and natron. The differences in sand composition can be attributed to the fact that different sources of sand were used for Levantine II glass compared to Levantine I glass. Sand for the production of Levantine II glass might have come from the Levantine coast rather than the Belus delta, since this was closer to the furnaces and might have been more cost effective. Another characteristic of Levantine II glass is the lower level of natron compared to the level of natron in Levantine I glass which was probably caused by restrictions and complications with its supply (Fiori and Vantini 2004, 167).

Fiori and Vantini (2004, 168) are convinced that no Levantine II objects have been found in contexts dating to a period earlier than the seventh century AD. Based on this evidence they suggest that Levantine II might have replaced Levantine I.

2.2.3 RNCBGY1 and 2

RNCBGY 1 and 2 (short for Roman Naturally Coloured Blue Green Yellow) are two glass groups dating to the first to fourth centuries AD. They are both naturally coloured, which means this group comprises blue-green and yellow glass. These two groups originate from the RBGY groups, Roman (naturally coloured) Blue Green Yellow glass (Gliozzo 2013, 624). The name changed into RNCBGY.

Both groups, RBGY 1 and RBGY 2, have intermediate levels of the elements natrium oxide (Na_2O), calcium oxide (CaO), alumina (Al_2O_3) and manganese (MnO). RBGY 2 can be distinguished from RBGY 1 because of its higher levels of silica (SiO_2) and potassium (K_2O) (Gliozzo 2013, 624).

The RNCBGY 1 group is compositionally similar to HIMT glass. However, the elements iron (Fe_2O_3), manganese (MnO) and titanium (TiO_2) are lower than the characteristic high levels of HIMT glass (Gliozzo 2013, 630). The composition of HIMT glass is described more elaborately in the following paragraph. Therefore, RNCBGY 1 is said to have a north African, possibly Egyptian, area of origin (Gliozzo *et al.* 2017, 716).
The composition of the RNCBGY 2 group is similar to Levantine glass and is therefore said to have an origin in the Syrian-Palestinian area (Gliozzo *et al.* 2017, 122, 131).

2.3 HIMT glass

The last couple of decades has seen a large increase in the amount of chemical research on glass assemblages, resulting in an extensive database of information and many opportunities to compare the different kinds of glass. From this information, several different subgroups of HIMT glasses have been distinguished (Ceglia 2015, 215). These are all characterized by their high but fluctuating levels of titanium (Ti), manganese (Mn), and iron (Fe). Furthermore, the different groups can be distinguished by their varying levels in calcium (CaO), which is dependent on the use of different sand sources (Ceglia 2015, 215). The first HIMT-like glass group was described in 1993 and published in an article by Mirti about the glass assemblage in Aosta, a region in northern Italy, where she distinguished 'Group E'. 'Groupe E' is a group of glass with the characteristics of HIMT glass. This group is dated to the fourth century AD and consists of vessel and window glass.

Besides the 'pure' HIMT groups, as described above, there are also combination groups for glasses that fall in between the values of either HIMT glass or another kind of glass. Examples are RNCBGY1/HIMT or HIMT/RNCBGY1 glasses (Gliozzo *et al.* 2016, 139).

2.3.1 Original HIMT

This type of glass was recognized for the first time by Freestone in 1994 during the analysis of glass from Carthage (Freestone 1994). It became clear that HIMT glass was characterized by high levels of iron (Fe) (>1%), manganese (Mn), and titanium (Ti) (>0.25%), complemented with the presence of high magnesium oxide (MgO) (>0.8%) and natrium oxide (Na_2O) (>16%), and generally a low calcium level (CaO) (<7%) (Freestone *et al.* 2018, 159; Juan Ares *et al.* 2019, 654). The pattern of the trace elements of original HIMT glass shows generally high levels of zirconium (Zr) and hafnium (Hf) in addition to barium (Ba) and strontium (Sr) (Gliozzo *et al.* 2016, 138).

Next to the fact that HIMT can be separated from Levantine I and II and Egypt I glasses on a chemical level, it also has a different colour. Raw HIMT glass is often yellow-green while glass from the Levant is commonly blue (Freestone *et al*. 2018, 159). For all HIMT groups, an Egyptian origin has been suggested due to high soda levels (De Juan Ares 2019, 651).

2.3.2 Groupe 1, 2 and 3

In 2003, Foy published a new work about HIMT glass. He defined three groups of HIMT glass; Groupe 1, Groupe 2 and Groupe 3, each with their own subgroups.

Groupe 1 consists of vessels, raw glass, and glass waste and generally dates to the fifth century AD. Groupe 1 has higher amounts of iron (Fe), titanium (Ti), and manganese (Mn) levels and a lower calcium oxide (CaO) level than Groupe 2.

Groupe 2 also comprises vessels, raw glass, and waste glass, but dates to the mid sixth to eighth century AD. Both groups are found in, among others, France, Tunisia, and Egypt (Ceglia *et al*. 2015, 215; Foy *et al*. 2003, 46). In order to determine the origin of the raw material of this glass group, a comparative research has been executed, from which could be concluded that the ingredients of raw glass of Groupe II as well as Groupe I do not show similarities with the raw materials from the coast of Anatolia, Cyprus, and Syria. Therefore, these regions can be excluded from the possibilities as primary production centres for Groupe 1 and Groupe 2. Based on the chemical composition, it seems that Groupe 1 has almost certainly an Egyptian provenance. The provenance of Groupe 2 stays uncertain (Foy *et al.* 2003, 47, 28).

Groupe 3 dates to the end of the fourth century AD until the end of the seventh or even beginning of the eighth century AD (Foy 2003, 62). Groupe 3 has three subgroups: Série 3.1, Série 3.2 and Série 3.3, which all have different compositions and provenances. Série 3.2, which is the most important subgroup of Groupe 3 (Foy *et al.* 2003) for this thesis, is dated to the period between the end of the fifth century AD until the beginning of the sixth century AD (Foy *et al.* 2003, 62). In an article, Foy *et al.* (2003, 64) state that this glass has a Levantine origin. However, according to Schibille *et al.* (2017, 1237), Série 3.2 and Série 2.1, which is a subgroup of Groupe 2, have an Egyptian provenance even though they have slightly lower titanium (TiO_2) levels than average HIMT glass. In comparison to glass with a Levantine origin, their titanium (TiO_2) and alumina (Al_2O_3) ratio is high enough to place their origin in Egypt.

2.3.3 HIMT 1 and 2

Jackson and Foster (2009) published an article on the composition of 'naturally coloured' late Roman glass in late Roman Britain. Many glass objects from their published assemblage belong to the HIMT glass group. In their research, Jackson and Foster separate two kinds of HIMT glass, named HIMT 1 and HIMT 2. HIMT 1 is seen as the stronger HIMT, since it contains on average double the levels of iron (Fe), manganese (Mn), and titanium (Ti) oxides compared to HIMT 2 glass. Also, several trace elements like magnesia (Mg), barium (Ba), chromium (Cr) and zirconium (Zr), are higher in HIMT 1 glass than in HIMT 2 glass. These elevated levels can be linked to the use of impure sand. The dating of HIMT 1 and 2 overlaps largely. However, it is suggested that HIMT 1 dates to mid to late fourth century AD, while HIMT 2 has some samples dating to 330 AD and onwards (Foster and Jackson 2009, 192-193).

Generally, weaker HIMT (HIMT 2) glass contains higher levels of lead (Pb) and copper (Cu), indicators for recycling, compared to stronger HIMT glass (HIMT 1) (Gallo *et al.* 2014, 15). This can be explained because recycling already fulfilled a large role in the glassmaking industry in Roman Britain. The input of new and therefore stronger HIMT glass was first mixed with already recycled glass, resulting in weak HIMT glass. Only until more HIMT glass was imported in Britain and the glass mixtures would contain more HIMT glass, the HIMT 1 glass group, which is the strongest of both groups, could be defined (Duckworth 2020, 33).

2.3.4 CaO-rich HIMT

This glass group shows similarities with the HIMT group. However, the CaO-rich HIMT group contains much higher levels of calcium oxide (CaO), and therefore shows more similarities to the Levantine glass composition (Gliozzo *et al.* 2016, 87, 97). Cao-rich HIMT glass seems to date between the first and tenth centuries AD. Most of the samples, however, date to the fourth to seventh centuries AD, similar to the general HIMT group. Even though this type of glass was widespread, from the Mediterranean to Great Britain, the majority of the excavated objects belonging to this glass group was found around the Adriatic Sea. The forms of the objects include tesserae, vessels, windows, rods, and chunks. The colours vary broadly from colourless to blue/green, but also more brownish-red to yellow and violet (Gliozzo *et al.* 2016, 98).

The trace elements of this glass group, particularly from the samples from Herdonia, differ from HIMT glass because of their lower zirconium (Zr) and hafnium (Hf) contents, possibly indicating a different provenance (Gliozzo *et al.* 2016, 102). The REE pattern falls in between Levantine and HIMT glass groups.

2.3.5 CaO-rich/Na_2O poor HIMT

This group has similar calcium oxide (CaO) values as the CaO-rich HIMT group. However, this glass is characterized by lower natrium oxide (NaO) levels compared to the general HIMT group. The trace element pattern falls, just like the CaO-rich HIMT group, in between the Levantine and HIMT glass groups. There is, however, a slightly higher similarity with HIMT glass than with Levantine glass (Gliozzo *et al.* 2016, 98).

2.3.6 Origin and dispersion of HIMT glass

For a long time it was not certain where HIMT glass was produced. However, currently it has been accepted that this type of glass originates in Egypt after which it was transported throughout the whole Mediterranean area and north western Europe where it was locally formed into objects. French and English researchers concluded this independently since this glass type has high levels of soda and titanium (Ti), characteristic for Egyptian glass, and was found in large numbers on Egyptian sites (Nenna 2014, 179, 180).

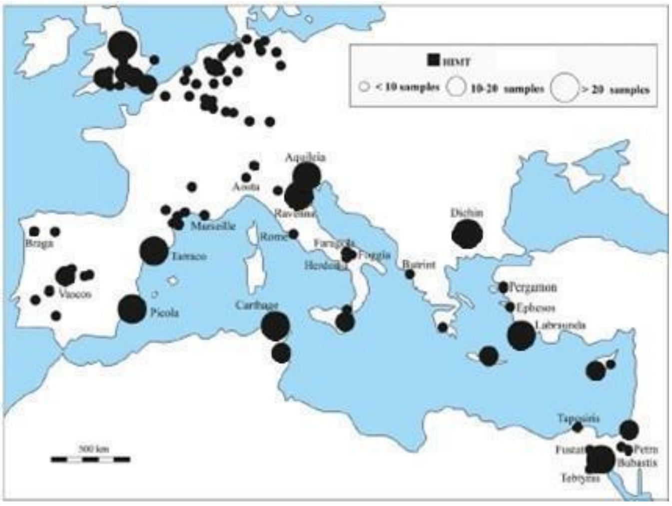

Figure 9: Dispersion HIMT glass after De Juan Ares et al. (2019).

Figure 9 shows the dispersion of HIMT glass. The map shows that HIMT glass was widespread throughout the Mediterranean and north western Europe, divided over a couple of larger centres and many small sites. This specific diversion might tell something about the trade routes during the fourth to seventh centuries AD and the relation between different geographical areas in this period. This information can be retrieved from the presence of HIMT glass in glass assemblages other than on their production site. It can tell about the amount of the glass that is transported, the routes that were used to get from the production site to other sites across the Mediterranean and North Western Europe and to what extent the influx of newly produced glass had on the current glass market and the recycling practices.

3. Case studies of HIMT glass in Italy

3.1 Overview sites with HIMT glass

HIMT glass became widespread in the Mediterranean area and north western Europe between the fourth to seventh century AD. One of the regions where HIMT glass is present, is Italy. In this section, an overview of the sites where HIMT glass was excavated will be provided based on several publications (fig. 10). The sites have been selected based on the presence of HIMT or glass with a similar chemical composition. Therefore, various forms of glass will be covered in this research, from tesserae[5] to vessels and windows. Furthermore, a distinction has been made between consumption and production sites based on the information described in the publications about the archaeological sites.

Figure 10: map of sites containing HIMT glass in Italy (own picture, based on google maps).

[5] Mosaic blocks.

3.2 Production sites

Grado and Vicenza [6]

Grado is a site in the northernmost coastal area of the Adriatic Sea. The analysed fragments come from the archaeological site called Fumolo. The site dates from the second/third to the 15th century AD (Silvestri *et al.* 2005, 799). Grado had a strategic position in between the Mediterranean area and the Danubian region[7]. Raw glass was probably imported to this site and reworked here at a secondary production centre. This can be concluded from the melting waste and test droplets found during excavations (Silvestri *et al.* 2005, 810-811).

Vincenzo is a town in the Veneto region. The glass fragments analysed come from the nearby situated archaeological area Pedemure S. Biagio. It has a very complex stratigraphy. The glass fragments from this excavation have a very wide dating, ranging from the first to 14th century AD. Most of the samples are tableware (Silvestri *et al.* 2005, 799).

The publication of these sites includes also the glass assemblage from Pozzuoli and the Iulia Felix shipwreck. Therefore, the information retrieved from the publication will also be partly about these two other sites. 81 samples originating from Vicenza, Grado, Pozzuoli, and the Iulia Felix shipwreck have been analysed, but only the sites of Vicenza and Grado yielded HIMT glass. The glasses dating to the Roman and early Medieval period are soda-lime-silica glass with a natron flux, while the late Medieval glasses have a plant ash flux (Silvestri *et al.* 2005, 803). Several groups have been distinguished but only the samples belonging to group A2/2 show similarities to 'Groupe 2' of Foy (*et al.* 2003). They date to the fifth to eight centuries AD and are all yellow coloured. Other glass finds from Grado and Vicenza can be labelled as Levantine I glass (Silvestri *et al.* 2005, 810).

---

[6] Silvestri, A., G. Molin and G. Salviulo, 2005. Roman and Medieval glass from the Italian area: bulk characterization and relationships with production technologies. *Archaeometry* 47(4), 797-816.

[7] The geographical area including the middle and lower Danube basins, the Eastern Alps, the Dinarides and the Balkans.

Classe, Ravenna[8]

Classe served as a harbour and was connected with the city of Ravenna by several canals. It was one of the most important trade centres between the fifth and eight centuries AD. The site consisted mostly of buildings (warehouses), streets, and canals. Many trade goods, like food or raw working materials, were stored here.

Two areas were excavated. The first one, building 6, was built during the beginning of the fifth century, and comprised a kiln and a large concentration of glass fragments including working wastes. The other excavated area was a small dump which dated between the end of the fifth and beginning of the sixth century AD. The dump is close to a warehouse, which burned down at the end of the fifth century AD (Maltoni *et al.* 2015, 1-3). In building 6, a total amount of 1.513 glass fragments have been excavated, including 973 working indicators and 540 fragments of vessels. The glass dates between the fifth and eighth centuries AD. From the dump excavation, 213 fragments of vessels were excavated including 16 glass working samples.

For the analysis, 57 samples were selected, consisting of 25 vessel fragments and 32 glass working wastes (Maltoni *et al.* 2015, 3,5). All samples are silica-lime-soda glass with natron as flux. After analysis, the 57 samples could be divided into three groups; CL1 (HIMT), CL2 (Levantine 1) and CL3 (Série 3.2). CL1 can also be split up in three subgroups, a, b and c. Subgroups a and b show similarities with 'strong' HIMT glass (HIMT 1), while c is compared best with 'weak' HIMT (HIMT 2) glass (Maltoni *et al.* 2015, 11, 13, 14). The colour of the HIMT glasses varies between (light-)blue, green, yellow, brown or colourless (Maltoni *et al.* 2015, 6). Isotopic research on the samples has proven that almost all fragments have a strontium (Sr) content between 366 and 584 ppm, indicating the use of coastal sand. However, the samples of the HIMT group (CL1) shows lower strontium (Sr) ratios, more similar to sand containing continental limestone and indicative for the use of impure coastal sand rich in non-carbonatic, strontium (Sr)-bearing silicatic minerals. Neodymium (Nd) values range between -5.38 ε_{Nd} and -3.91 ε_{Nd}, indicating an eastern Mediterranean provenance (Maltoni *et al.* 2015, 16).

[8] Maltoni, S., T. Chinni, M. Vandini, E. Cirelli, A. Silvestri and G. Molin, 2015. Archaeological and archaeometric study of the glass finds from the ancient harbour of Classe (Ravenna-Italy): new evidence. *Heritage Science* (3) 13, 1-19. DOI 10.1186/s40494-015-0034-5

Palatine Hill, Rome, Lazio [9]

On the north east slope of the Palatine Hill, we can find the remains of the Domus Aurea, an Imperial complex constructed by command of the emperor Nero just after 64 AD. Two basement rooms of this complex, which seem to be suddenly abandoned during the second half of the fifth century AD, yielded 46.000 pottery fragments and 2.200 glass fragments dating to the Late Antiquity (Gliozzo *et al.* 2017, 709-710).

The glass fragments, from which 20 were analysed, included both objects and production samples. All objects were silica-soda-lime glass with natron as a fluxing agent. From the raw glass, six objects are labelled as HIMT glass. They have a yellow colour with either brownish or greenish tints. Five object fragments, consisting of a collar and waste fragments, are almost all HIMT glass. Only one sample is seen as 'pure' HIMT while the rest is similar to both HIMT and RNCBGY 1 glass. Four out of the five fragments have a (light) green colour, only one shows a reddish colour. Five vessel glass fragments are indicated as HIMT glass, with a green or yellow-green colour (Gliozzo *et al.* 2017, 723).

Only two Levantine samples and three of the five vessel fragments are 'fresh' glass. The other ones show signs of recycling. Levels of copper (Cu), lead (Pb), and antimony (Sb) between 100 and 1000 ppm are seen as indicative for recycling, and these values are present in most of the objects from this site (Gliozzo *et al.* 2017, 724).

Herdonia, Foggia[10]

Herdonia was a settlement located near the Via Traiana, which was part of a large regional and inter-regional connection system. This was part of the reason that during the second to fourth centuries AD the city prospered. Between the second half of the fourth until the late fifth centuries AD, the city knew a period of decline. However, the presence of a bishop caused the continuation of some of the old prosperity between the late fifth and early sixth centuries AD (Gliozzo *et al*. 2016, 82).

---

[9] Gliozzo, E., B. Lepri, L. Saguì and I. Memmi, 2017. Glass ingots, raw chunks, glass wastes and vessels from 5th century AD Palatine Hill (Rome, Italy). *Archaeological Anthropological Science* 9 (5), 709-725.

[10] Gliozzo, E., M. Turchiano, F. Giannetti and A. Santagostino Barbone, 2016. Late Antique glass vessels and production indicators from the town of Herdonia (Foggia, Italy): New data on CaO-rich/weak HIMT glass. *Archaeometry* 58 (1), 81-112. doi: 10.1111/arcm.12219

Of the nearly 4.000 glass fragments that have been excavated at Herdonia, 48 have been analysed. The fragments come from two domus complexes and a thermal complex, dating to the fourth and fifth centuries AD. The analysed samples can be divided in several compositional groups: HIMT, Levantine 1, RNCBGY1, RNCBGY2, RC/LAC-Sb, intermediate HIMT/RNCBGY1, intermediate RNCBGY1/HIMT, intermediate Levantine/RNCBGY2 and two other groups, the CaO-rich HIMT and the CaO-rich/Na_2O poor HIMT, with Egypt as the most prominent provenance for the raw glass. All the samples have siliceous sand as vitrifying agent and the used flux was natron (Gliozzo *et al.* 2016, 81-85).

Only five of the 48 samples are labelled as pure HIMT glass. Three other fragments are doubtful, for they show similar composition except for their high silica (SiO_2) and low natron levels. These five samples show copper (Cu) and/or lead (Pb) and/or antimony (Sb) levels that indicate recycling. The colour of these samples ranges between yellow, yellow-green and green/aqua, and their forms comprise raw glass, bowls/plates, a lamp, a beaker/lamp, a jug/bottle, and two bottoms. The REE data shows that all fragments are similar to HIMT glass (Gliozzo *et al.* 2016, 90-91, 94).

Intermediate RNCBGY 1/HIMT and intermediate HIMT/RNCBGY 1 together consist of ten samples. Their colours range between colourless to yellow, to yellow-green and green. Forms of the objects comprise lamps, beakers, and beaker/lamps. For both groups the REE pattern is similar to HIMT glass. Intermediate RNCBGY 1/HIMT has indications for recycling, while intermediate HIMT/RNCBGY 1 group does not show signs of recycling (Gliozzo *et al.* 2016, 96-97).

The four samples belonging to CaO-rich HIMT consists of a colourless goblet, a colourless and light-yellow lamp and a light yellow beaker. At least two of the four samples show signs of recycling. The REE pattern of this group lies between the values of the Levantine and HIMT groups (Gliozzo *et al.* 2016, 97-98).

The CaO-rich/Na_2O-poor HIMT group contains four samples; a jug/bottle, a yellow-green lamp, a colourless goblet and a light-yellow beaker/lamp. Its REE pattern lies again in between the Levantine and HIMT groups, leaning more to HIMT values than to Levantine glass (Gliozzo *et al.* 2016, 98).

A possible local production centre may have been established here. The similar morphological types of the glass assemblages of Faragola and Herdonia might indicate the reworking of HIMT glasses (Gliozzo *et al.* 2016, 143).

Piazza Bovio, Naples[11]

Excavations located closely to Piazza Bovio show the presence of artisan workshops, which are dated to the sixth century AD. One of those workshops was a glass factory, where archaeological evidence has been found for the production and recycling of glass objects, including fragments, fuel ash slag, charcoal, and a small dismantled furnace (De Francesco *et al.* 2014, 138).

In total, 1.789 glass fragments have been excavated, from which 799 fragments indicate glass production. 18 fragments have been selected for research. The selected fragments comprise glass scraps and finished products from which the colour varies between blue-green, dark green and yellow, and date to the sixth to seventh centuries AD (De Francesco *et al.* 2014, 137-138). From the analysis it can be concluded that the glass is soda-silica-lime glass with natron as a flux. Three groups could be distinguished, from which one of the groups, the N1 group, is similar to HIMT glass. The samples, two raw glass fragments, two chalice feet, and a lamp rim, all have a dark green or yellow colour. These samples show high levels of iron (Fe), manganese (Mn) and titanium (Ti). Furthermore, the level of zirconium (Zr) is also similarly elevated as seen in HIMT glass (De Francesco *et al.* 2014, 140, 144). The other glass groups, N3 blue-green glass group and the N2 colourless glass group, can respectively be associated with Levantine I glass and the colourless 2a 'manganese-decolourised' group from Foster and Jackson (2010) (De Francesco *et al.* 2014, 145).

Catania, Sicily [12]

The Roman amphitheatre of Catania dates, based on material finds, to the Late Imperial and Proto-Byzantine period (the fourth to sixth centuries AD). The amphitheatre could probably accommodate ten to fifteen thousand people and was known for the

[11] De Francesco, A.M., R. Scarpelli, F. Del Vecchio and D. Giampaola, 2014. Analysis of Early Medieval glass from excavations at 'Piazza Bovio', Naples. *Archeaometry* 56 (1), 137-147.
[12] Di Bella, M., C. Giacobbe, S. Quartieri, G. Sabatino and U. Spigo, 2015. Archaeometric characterization of Proto-Byzantine glass workshop from the Roman amphitheatre of Catania (Sicily, Italy). *European Journal of Mineralogy* 27 (3), 353-363. DOI: 10.1127/ejm/2015/0027-2449

‘naumachy’[13]. Two areas, IX and X, which are located in the northeast sector of the theatre, were re-used for habitational purposes and as workshops. This can be concluded from the excavation of burnt patches and stones, metallic tools, indications of fire and large amounts of glass fragments indicating production processes (Di Bella *et al.* 2015, 353-354).

In total, 25 excavated glass samples have been analysed. These glass samples comprised object fragments, molten glass, and glass drops. They are natron-based glass and could be divided in two chemically distinct groups: HIMT (20 samples) and Levantine I glass (three samples). The assemblage also contained a pure obsidian fragment and an indeterminable sample (Di Bella *et al*. 2015, 361). The colour of the HIMT glasses include several shades of blue, green and brown, and a few colourless samples (Di Bella *et al.* 2015, 356). The average REE pattern seems to be more enriched than the regular soda-lime glasses, which indicates the use of sandy raw materials with heavy mineral levels. Furthermore, the levels of strontium (Sr) are also very high, indicating the use of Mediterranean coastal sand (Di Bella *et al.* 2015, 359).

3.3 Consumption sites

Rocca di Asolo, Veneto [14]

Rocca di Asolo is a settlement in northern Italy. It was already occupied during the ninth century BC and its inhabitation continued until the 16h century AD. During the late medieval period, its function changed to a military fortification.

During excavations, several layers were uncovered and in total circa 7.000 glass fragments have been unearthed. Only about 100 from the 7.000 glass pieces date to the early Middle Ages. 33 fragments have been analysed, varying from windowpanes to beakers and bottles. The windowpanes include eight pieces dating to the early Middle Ages (7-10th centuries AD) and the other four to the late Middle Ages (15th century AD). The beakers and bottles all date to the late Middle Ages (12th-15th centuries AD), which is too late for HIMT glass. The colour of the panes varies between pale blue, greenish, yellowish, and pale brown (Gallo and Silvestri 2012, 1024-1025).

---

[13] Real naval battles in the theatre.

[14] Gallo, F. and A. Silvestri, 2012. Medieval Glass from Rocca di Asolo (Northern Italy): An archaeometric study. *Archaeometry* 54 (6), 1023-1039.

Six out of eight windowpanes can be assigned to the HIMT group. They are soda-lime-silica glass with a natron flux. Furthermore, they have heightened levels of iron (Fe), manganese (Mn), magnesium (Mg) and a positive correlation between iron (Fe) and aluminium (Al). The colour of these panes is green or yellowish-brown. The other two windowpanes are similar to the 'Groupe 3' of Foy *et al.* (2003) and seem to be recycled Roman glass (Gallo and Silvestri 2012, 1027-1029, 1036).

Casa delle Bestie Ferite, Aquileia, Udine[15]

Aquileia was a colony in north-east Italy and founded in 180-181BC. It is connected to the rest of Italy by a road system and the river Natisone. It was part of a large trade system that connected Italy, the Po Plain, and transalpine regions. Many kinds of goods like wine, oil, livestock, timber, iron, food, clothing, pottery, and glassware were transported from and to the city. The excavated glassware is represented by finds from different ages, types, and colours. No glass production furnaces have been found in the city. However, glass waste, chunks, and debris do have been found, which might still indicate secondary production, even though it has never been confirmed by definite archaeological finds (Gallo *et al.* 2014, 7; Maltoni *et al.* 2016, 2).

One of the houses located in Aquileia, Casa delle Bestie Ferite, yielded many glass fragments. The house was quite large, occupying 800m^2 and located in the northern part of the city near one of the larger roads. It was occupied from the first to seventh century AD (Gallo *et al.* 2014, 8-9). From the 688 glass fragments found in this house, 62 have been analysed for this study. They can be dated to the late third to sixth centuries AD. All analysed fragments are soda-lime-silica glass with natron as flux. After the analysis, the glass assemblage can be divided in three groups, AQ/1(a or b), AQ/2 (a or b) and AQ/3. AQ/1, compositionally similar to HIMT glass, comprises 38 samples. These include bottles, beakers, cups and a lamp. They generally date to the late third to early fifth centuries AD and are yellow/green coloured. AQ/1b can be compared to the 'stronger' HIMT literature groups, like Group 1 from Foy *et al.* (2003). AQ/1a has higher levels of iron (Fe), titanium (Ti), nickel (Ni), and vanadium (V), and is seen as the stronger HIMT group in Aquileia. However, it does not show any comparisons with HIMT groups from

[15] Gallo, F., A. Marcante, A. Silvestri and G. Molin, 2014. The glass of the "Casa delle Bestie Ferite": a first systematic archaeometric study on Late Roman vessels from Aquileia. *Journal of Archaeological Science* 41, 7-20.

the literature, which might indicate the presence of a new variation of the HIMT glass (Gallo *et al.* 2014, 11). Group AQ/2 has a chemical composition very similar to Levantine I glass. AQ/3 is distinguishable by the low calcium-low alumina levels in its composition (Gallo *et al.* 2014, 9-12).

The research on chemical composition also indicated that, generally, the glass from Aquileia was barely recycled. However, in the HIMT group, AQ/1, 28 out of 37 objects show traces of recycling. The 'weaker' HIMT group (AQ/1b) has higher copper (Cu) and lead (Pb) levels than the 'stronger' HIMT group (AQ/1a). This indicates more recycling of the 'weaker' HIMT group (Gallo *et al.* 2014, 15).

Domus of Tito Macro, Aquileia, Udine[16]

The Domus of Tito Macro was the only example of an *atrium domus*[17] identified in Aquileia. It is situated in the southern part of the town and was probably constructed around the first century AD and used until the seventh century AD. During excavations, more than 900 glass fragments were unearthed, from which 74 were used as samples for chemical analysis. The samples comprise vessels, chunks, and wastes in colourless, intentionally-coloured (dark-blue and amber-yellow), and naturally coloured (blue, green or yellow) glass. All samples are silica-soda-lime glasses with natron as fluxing agent (Maltoni *et al.* 2016, 2, 5).

After analysis, the samples have been divided in several groups based on composition, such as decoloured groups, a coloured group, HIMT/HIT[18] glass, Levantine glass, and Série 3.2 (Maltoni *et al.* 2016, 7). The HIMT group consists of 26 samples, among which two chunks of glass and 24 vessels. The vessels consist of various forms, cups, beakers, bowls, flasks, dishes, lamps, and stemmed goblets. Most of the vessels are naturally green or yellow, but three vessels are dark blue. High levels of soda, iron (Fe), manganese (Mn), and titanium (Ti) are found in the composition of these glasses, and also the trace elements strontium (Sr), zirconium (Zr), barium (Ba), chromium (Cr), vanadium (V), and nickel (Ni) have heightened values. These high levels show similarities

[16] Maltoni, S., A. Silvestri, A. Marcante and G. Molin, 2016. The transition from Roman to Late Antique glass: new insights from the Domus of Tito Macro in Aquileia (Italy). *Journal of Archaeological Science* 73, 1-16.
[17] A large Roman house which contained a central space around which the rooms were situated. The central space is also known as atrium.
[18] HIT stands for High Iron and Titanium glass.

with the HIMT group of Freestone. Furthermore, the overall low levels of cobalt (Co), copper (Cu), zinc (Zn), antimony (Sb), and lead (Pb) indicate that there was a limited extent of recycling in this group of glasses. Neodymium (Nd) values range between -5.5 ε_{Nd} and -3.5 ε_{Nd} indicative for the use of sand in the Eastern Mediterranean. The strontium (Sr) isotopic ratio ranges between 0.7092 and 0.7081, which shows the use of sand rich in mollusc shells. The HIMT glass seems to have lower strontium (Sr) values. This indicates that its strontium (Sr) ratio was influenced by not only mollusc shells, but also by other manganese (Mg), iron (Fe), titanium (Ti)- bearing minerals found in more impure coastal sand or inland sediments. These were often seen in Nile delta sand (Maltoni *et al.* 2016, 12, 14).

The HIMT group can be split between 'very strong' HIMT samples with very high iron (Fe) levels, and samples which have lower levels and show more similarity with the original HIMT group. In general, HIMT glass dominates the glass assemblage found in this atrium house (Maltoni *et al.* 2016, 8).

Chapel of St. Prosdocimus, Basilica of St. Justine, Padova[19]

The Basilica of St. Justine is located in the region of Padova. It was constructed during the fourth century AD. During the sixth century AD, this basilica was extended with a votive chapel dedicated to St. Prosdocimus, the first bishop of Padova. In 1958, approximately 3.000 mosaic tesserae[20] were excavated. They were grouped in eight colour types: white, yellow, orange, red, brown, green, blue, and gold. They are shaped in small squares, around 1 cm for the side lengths (Silvestri *et al.* 2011, 3403).

200 tesserae have been analysed and can be divided in three main groups. Two of these groups are soda-silica-lime glass with natron as flux. The other group, consisting of only three samples, are made with plant ash. One of the first two groups is comparable with the 'Roman' colourless or unintentionally coloured glass, dating to the first to fourth centuries AD (Silvestri *et al.* 2011, 3405). The other group with natron as a flux is chemically comparable with HIMT glass. This group can be split up in two subgroups. One of them is similar to HIMT glass dating to the mid-fourth to fifth century AD. The

[19] Silvestri, A., S. Tonietto and G. Molin, 2011. The paleao-Christian glass mosaic of St. Prosdocimus (Padova, Italy): archaeometric characterisation of 'gold' tesserae. *Journal of Archaeological Science* 38, 3401-3414. doi:10.1016/j.jas.2011.07.027

[20] Small square pieces of glass, stone or ceramic used in the production of mosaic pieces.

other subgroup shows similarities to weaker HIMT glass such as ‘Groupe 2’ (Foy *et al.* 2003) and HIMT 1 glass (Foster and Jackson 2009), apart from its higher calcium oxide (CaO) contents. This latter group is dated to the sixth to eighth centuries AD (Silvestri *et al*. 2011, 3412).

Mevaniola, Galatea, Pianetto [21]

Near Galatea, a Roman municipium was situated, called Mevaniola. The site yielded several public buildings, however, no private houses were identified. Even though no private houses were found, the site was probably inhabited between the first to third centuries AD, with a possible extension to the end of the fourth century AD. There were only a few window glass fragments found in the excavations, without a clear context, from which ten samples have been analysed. The colours from the glass finds vary from light- to blue-green. All the samples date to the Roman Imperial period (Arletti *et al.* 2010, 258).

Four glass fragments show a distinguishable chemical composition. They are silica-soda-lime glass, in which natron was used as a flux. These glasses have heightened levels of calcium oxide (CaO), titanium (Ti), iron (Fe) and manganese (Mn), which is indicative for HIMT glass. Similar to the glass from Theorodic’s villa, these levels are higher than seen in other late Roman glass, but still distinctly lower than other late Roman HIMT glass samples (Arletti *et al.* 2010, 267-268). This can be a possible indication of the mixing of ‘regular’ late Roman glass with HIMT glass. Three of these samples have heightened levels of the strontium (Sr) and zirconium (Zr) isotopes, confirming the presence of HIMT glass (Arletti *et al.* 2010, 266).

Lastly, the other fragments show high levels of manganese (Mn), and low levels of iron (Fe), or low levels of both these elements (Arletti *et al.* 2010, 264).

San Genesio, Tuscany[22]

The settlement of San Genesio, dating between the sixth century BC and the 13th century AD, is situated in between Pisa and Florence. The settlement was part of a large

[21] Arletti, R., G. Vezzalini, S. Benati, L. Mazzeo Saracino and A. Gamberini, 2010. Roman Window glass: a comparison of finding from three different Italian sites. *Archaeometry* 52 (2), 252-271.
[22] Cagno, S., L. Favaretto, M. Mendera, A. Izmer, F. Vanhaecke and K. Janssens, 2012. Evidence of early medieval soda ash in the archaeological site of San Genesio (Tuscany). *Journal of Archaeological Science* 39, 1540-1552.

trade system because of its location near Roman and pilgrim roads and many rivers. The surroundings of the city were also very fruitful for raw material supply for the ceramic industry (Cagno *et al.* 2012, *1542*). No glass working evidence in the sense of build structures has been found at San Genesio. However, there are some other finds, such as colorants, glass fragments, and the presence of metal working facilities, that might contradict the supposed absence of glass working on this site (Cagno *et al.* 2012, 1548).

In total, 37 glass fragments have been analysed. This selection comprises solely drinking vessels, which are dated between the fourth and eleventh centuries AD. The colours differ from blue, green, brown to colourless, with some decoration of opaque threads. The glass samples are all silica-soda-lime glasses. The calcium (CaO) and alumina (Al_2O_3) levels seem to be similar to the values of these elements as seen in HIMT glass (Cagno *et al.* 2012, 1542-1544). Even though all samples might be similar to HIMT glass, the analysed glass fragments have been divided into three groups. The SG1 glass group consists of green-blue vessels dating to the sixth to eighth centuries AD and some lamps dating up to the 11th century AD. These objects can be assigned to the HIMT 2 group (Cagno *et al.* 2012, 1546). The SG2a group, comprising lightly coloured drinking vessels of the sixth to seventh centuries AD and one lamp from between sixth to eleventh centuries AD, was probably a mixture of raw glass belonging to Groupe 2 (Foy *et al.* 2003) and HIMT 2 (Jackson and Foster 2009). SG2b samples, olive-green glasses, seem similar to 'strong HIMT' glass. They are characterised by high levels of manganese (Mn) and iron (Fe), like Groupe 1 described by Foy *et al*. (2003) and the HIMT glass found at Sicily published by Arletti *et al.* (2010) (Cagno *et al.* 2012, 1547). The SG3 group, made with a soda ash flux, might have been made with raw material similar to Groupe 2 glass or HIMT 1. This kind of glass is very rare in north Italy in the sixth to seventh centuries AD (Cagno *et al.* 2012, 1548).

San Giusto, Foggia[23]

The excavations of San Giusto are located in north central Apulia and comprise the remains of a middle Imperial villa, a basilica and cemetery dating to the fifth and sixth centuries AD. The villa shows facilities for ceramic production, metal working, the

---

[23] Gliozzo, E., E. Braschi, F. Gianetti, A. Lagone and M. Turchiano, 2019. New geochemical and isotopic insights into the Late Antique Apulian glass and the HIMT1 and HIMT 2 productions – the glass vessels from San Giusto (Foggia, Italy) and the diagrams for provenance studies. *Archaeological Anthropological Science* 11, 141-170. DOI 10.1007/s12520-017-0531-4

processing of wool and sheepskin, and the storage of wine and grain. Furthermore, many glass fragments have been found dating to the fourth to ninth centuries AD. Even though there is a large presence of production processes, the site does not show indication for glass production (Gliozzo *et al.* 2019, 142).

From 1.323 excavated glass fragments, 35 have been analysed on a chemical level. 27 analysed fragments show very little to no indication for recycling, five samples can be indicated as recycled glass and the remainders are either recycled or intentionally coloured. The composition of the glass shows that the objects have been made with impure sands coming from different sources as vitrifying agents. Lime was used as a stabilising agent and natron as a flux (Gliozzo *et al.* 2019, 153).

The samples have been assigned to three chemically distinct groups, HIMT 1 (seven samples), HIMT 2 (eight samples) and Levantine glass (13 samples). The remaining fragments cannot be put in a group with certainty (Gliozzo *et al.* 2019, 158). The HIMT glasses are almost all a shade of yellow or green (Gliozzo *et al.* 2019, 143).

Ten samples have also been researched on an isotopic level. The strontium ratio ($^{87}Sr/^{86}Sr$) varies between 0.7084 and 0.7090, remaining below the modern seawater isotopic value (0.70917). It is generally lower than the strontium (Sr) ration that HIMT glass normally shows and is more compatible with the Levantine glass. However, there is a wide variation between the strontium (Sr) ratios, which indicates a possible heterogeneity of the sources of the raw materials (Gliozzo *et al.* 2019, 158-160). Neodymium (Nd) values range between -4.50 ε_{Nd} and -5.89 ε_{Nd}. These values correspond to the Syro-Palestinian and HIMT 2 glass groups (Gliozzo *et al.* 2019, 158-160).

Faragola, Apulia[24]

Faragola is a large rural villa complex, which was part of a large trade system, for it was located along the Via Aurelia Aeclanensis. The villa was occupied until the late Antiquity after which a period of abandonment followed. From the seventh century AD onwards, people reoccupied the villa complex (Gliozzo *et al.* 2016, 113-114).

[24] Gliozzo, E., M. Turchiano, F. Giannetti and I. Memmi, 2016. Late Antique and Early Medieval Glass vessels from Faragola (Italy). *Archaeometry* 58, 113-147. doi: 10.1111/arcm.12242

32 glass samples were analysed. They showed siliceous sands as probable vitrifying agent, and natron as the fluxing agent (Gliozzo *et al.* 2017, 123). The glass samples were divided in several groups according to chemical composition and its origin: Levantine, RNCBGY 2, RC/LAC-Sb, HIMT, RNCBGY 1, RNCBGY 1/HIMT and CaO-rich HIMT (Gliozzo *et al.* 2016, 133).

Three of the 32 samples were assigned to the HIMT glass group. They are made of yellow-green and brown glass. The forms comprise a glass bottom resting on multiple filaments, a bowl/plate, and jug/bottle. The fragments also contain high levels of copper (Cu), lead (Pb), and antimony (Sb), which indicates the possible practice of recycling. The REE pattern of these three objects are very similar to the HIMT REE pattern; high amounts of zirconium (Zr) and hafnium (Hf) in addition to barium (Ba) and strontium (Sr) (Gliozzo *et al.* 2017, 138).

Two samples of the Faragola samples, both lamps with a yellow-green and a light-yellow colour, show traits of both HIMT and the RNCBGY 1 glass. It might be an indication for a different area of origin. However, the generally accepted area of provenance remains north Africa, with Egypt as a more specific region. The REE pattern shows also that one of the two samples is similar to Levantine production, while the other is more similar to HIMT glass based on the barium (Ba), zirconium (Zr) and hafnium (Hf) levels (Gliozzo *et al.* 2017, 139).

Eleven samples are assigned to the group CaO-rich HIMT glass. This part of the assemblage is very diverse in terms of form, colour, and provenance. It comprises blue, colourless-to-yellowish, yellow, and emerald green samples. Moreover, the form varies between goblets, jug/bottles, beaker/lamps, and lamps, and the REE pattern of this group lies between that of Levantine and HIMT glass (Gliozzo *et al.* 2017, 141).

Ganzirri, Sicily[25]

Near Ganzirri Village, which is located close to Messina on Sicily, a late Roman settlement has been discovered. The settlement is dated to the late Roman-Byzantine period, and seemed to be inhabited between mid-fourth to late seventh centuries AD.

[25] Arletti, R., C. Giacobbe, S. Quartieri, G. Sabatino, G. Tigano, M. Triscari and G. Vezzalini, 2010. Archaeometrical investigation of Sicilian Early Byzantine glass: Chemical and Spectroscopic data. *Archaeometry* 51 (1), 99-114.

The ceramic finds from the excavation indicated that the site was part of a large trade system and received goods from North Africa, Eastern Mediterranean areas, and other Sicilian and Calabrian sites (Arletti *et al.* 2010, 99). Next to the excavated ceramic finds, glass fragments have been found. Eight fragments were analysed by Arletti *et al.* (2010, 100). They were retrieved from excavations in a domestic context, 'casa 7' described in Tigano (2002). Most of the forms were determined to be Isings 111 (cups/beakers).

Chemical analysis showed that the glass finds all have a silica-soda-lime composition, with natron as flux. Four of the eight fragments have an olive-green colour and have a lower level calcium (CaO) than the rest of the glass objects. Furthermore, they are characterized by high iron (Fe), titanium (Ti) and manganese (Mn) levels, which are clear indications of HIMT glass. All the other samples can be determined as Levantine I glass (Arletti *et al.* 2010, 105). Furthermore, the REE, zirconium (Zr), barium (Ba), and hafnium (Hf) levels of the HIMT group are higher than the levels found in the Levantine I groups (Arletti *et al.* 2010, 109-110). Some of the fragments show signs of recycling, based on the level of antimony (Sb) in the glass, which might be an indication of the use of older antimony decolourized glass in the recycling process (Arletti *et al.* 2010, 109).

Theodoric's Villa, Galatea[26]

Near the site of Galeata, Forlì-Cesena, Theodoric's villa was excavated. This villa has been dated to the beginning of the sixth century AD, with deeper layers dating to the Early Roman Imperial Age. Most excavated finds were fragmented, but a large amount of window glass could be distinguished. Thirteen samples have been analysed including two fragments dating to the Roman Imperial Age, and eleven more recent. Several panes date to the sixth century AD (Arletti *et al.* 2010, 253, 259) All samples were discovered in the bath area of the villa.

The composition of the glass fragments show that they are silica-soda-lime glass with natron as flux. Furthermore, all the panes, except for two samples, show high values of calcium oxide (CaO), titanium (Ti), iron (Fe), and manganese (Mn) (Arletti *et al.* 2010, 267). These levels, even though higher than seen in other late Roman glass, are still distinctly lower than other late Roman HIMT glass samples (Arletti *et al.* 2010, 268). This

[26] Arletti, R., G. Vezzalini, S. Benati, L. Mazzeo Saracino and A. Gamberini, 2010. Roman Window glass: a comparison of finding from three different Italian sites. *Archaeometry* 52 (2), 252-271.

can be interpreted as a possible indication for mixing the ‘regular’ late Roman glass with HIMT glass during recycling processes. The colours of the panes made of HIMT glass vary between light-green, green-olive, colourless and purple. Isotopic research on these panes show the presence of high levels of REE elements, including strontium (Sr) and zirconium (Zr), which is characteristic for HIMT glass (Arletti *et al.* 2010, 266).

Lastly, the other fragments show high levels of manganese (Mn), and low levels of iron (Fe), or low levels of both these elements (Arletti *et al.* 2010, 264).

3.4 Results

SITE	GANZIRRI	GALATEA	MEVANIOLA	SAN GENESIO	PIAZZA BOVIO	ROCCA DI ASOLO	CASA DELLE BESTIE FERITE	DOMUS OF TITO MACRO	CATANIA	PALATINE HILL	FARAGOLA	HERDONIA	CLASSE	ST. PROSDOCIMU	SAN GIUSTO	GRADO & VICENZA	TOTAL
NATURE OF SITE	C	C	C	C	P	C	C	C	P	P	C	P	C	C	C	P	
ROMAN IMPERIAL AGE		2	6														8
HIMT	4	11	4		5	6		26		12	3	8		15			94
HIMT 1							7		18					9	7		41
HIMT 2				12			31		2						7		52
CAO RICH HIMT											11	4					15
CAO RICH-NA2O POOR HIMT												4					4
GROUPE 1													24				24
GROUPE 2				12												10	22
SÉRIE 2.1													2				2
GROUPE 3						2										35 (incl. Iulia Felix and Pozzuoli)	37
SÉRIE 3.2							9	7					25	20			61
RNCBGY 1										2	1	1					4
RNCBGY 2											1	3					4
RNCBGY 1/HIMT										3	2	5					10
HIMT/RNCBGY 1												5					5
LEVANTINE/RNCBGY 2												2					2
RC/LAC-SB											8	5					13
MN-DECOLOURIZED					5			10									15
SB-DECOLOURIZED								7									7
MN+SB DECOLOURIZED								6									6
ROMAN DECOLOURIZED														49			49
COLOURED								8									8
LEVANTINE I	4				6		15	5	3	2	6	7			13	6 (Grado)	67
LEVANTINE II					2								6				8
EGYPTIAN PROVENANCE															3		3
LEVANTINE PROVENANCE															5		5
RAQQA/EARLY VENETIAN				5		30											35
ISLAMIC GLASS																12	12
PLANTASH												2		3		2 (Vicenza)	7
TOTAL	8	13	10	29	18	38	62	69	23	19	32	46	57	96	35	65	620

Table 1: Overview of number of glass objects per compositional group. C = consumption site; P = production site.

Based on the descriptions of the sites containing HIMT glass, it can be concluded that the sites are widely spread across Italy. Most of the sites are located on the eastern side of Italy, along the Adriatic coast. However, also larger cities on the west coast, such as Rome and Naples yield HIMT glass. Furthermore, Sicily, which had connections with trade routes across the Mediterranean, also shows the presence of HIMT glass. What needs to be taken into account is that the dispersion of the sites in this research are based on a limited amount of publications, so the reality might have been different.

Six out of the 17 sites yield remains of secondary production (Piazza Bovio (Naples), Palatine Hill (Rome), Catania, Herdonia, Grado and Vicenza). A production site can be distinguished by the presence of production waste, the remains of a furnace, and at Catania even metal instruments. The production sites included in this thesis are all located near the coast, both on the west and east side of Italy. Even though it would be logical that these production sites also show indicators of recycling, because recycling took place at production sites since there were all the tools for forming glass, not all of them yield recycled glass fragments, like, for example, Catania. There are more consumption sites than production sites showing indications of recycling in their glass assemblage. The Palatine Hill (Rome), Herdonia, Piazza Bovio (Naples), Rocca del Asolo, Casa delle Beste Ferite, San Giusto, Faragola (possibly), Ganzirri and Theodoric's villa yield remains of recycled glass objects.

None of the glass assemblages yield solely HIMT glass but comprise multiple glass groups as can be seen in table 1. From the 17 described sites, 11 show glass finds with a Levantine origin (meaning Levantine I, Levantine II or Levantine provenance) next to the HIMT fragments. Other glass groups that have been found are Roman Imperial age (two sites), RNCBGY1/2 and Levantine/RNCBGY 2 (three sites), Mn-decolourized (two sites), Sb-decolourized (one site), Mn+Sb decolourized (one site), Roman decolourized (one site), Egyptian provenance (one site), and coloured (one site). Furthermore, there are some later glass groups like Raqqa/Early Venetian (two sites), Islamic glass (one site), and plant ash glass (three sites).

The HIMT glass group can be separated into subgroups. The subgroups that are considered in this thesis are based on the descriptions from the publications of the researched sites. Regular HIMT glass has been described in 11 publications. Furthermore, HIMT 1 (strong HIMT) and HIMT 2 (weak HIMT) are considered in five publications. At both sites in Aquileia, but also in Classe, San Genesio and San Giusto, strong HIMT has been discovered. Weak HIMT has been distinguished at Classe, San Giusto, San Genesio, and Casa delle Beste Ferite. CaO rich HIMT and CaO rich-Na_2O poor HIMT are distinguished at only two sites, Faragola and Herdonia. The glasses from Theodoric's villa, Mevaniola, and the Basilica of St. Justine also show HIMT glass with high levels of calcium (CaO), however, these glasses are not labelled as CaO-rich HIMT glass. Moreover, the groups described by Foy (2003), Groupe 1, Groupe 2 (including Série 2.1) and Groupe 3 (including Série 3.2) are seen at eight sites: Classe, both sites from Aquileia, Rocca di Asolo, San Genesio, St. Prosdocimus, Grado, and Vicenza. Lastly, the RNCBGY groups are also seen in combination with HIMT. These subgroups have been found at three sites; the Palatine Hill, Herdonia, and Faragola.

4. Discussion

The previous chapter has provided an overview of archaeological sites in Italy containing HIMT glass. The only requirements for the selection of these sites was their location on the Italian peninsula and Sicily and the presence of HIMT glass. The analysed archaeological sites can therefore be either a consumption or a production site and comprise a wide variety of analysed objects and sites. This research has been done based on the available literary sources. This chapter will combine the data from the case studies with the general geopolitical developments of the fourth to seventh centuries AD in Italy and the Mediterranean, focussing on three larger themes: glass trade overseas, trade in Italy, and recycling. This will be done in order to reconstruct the dispersion of HIMT glass on the Italian peninsula and to understand what factors influenced the dispersion of HIMT glass.

4.1 Glass trade overseas

Figure 11: overseas trade routes during Roman period (ca. 125 AD) (https://transportgeography.org/).

The maritime trade network played an important role in the trade system during the Imperial Roman period around ca. 125 AD, as can be seen in figure 11. This continued during the fourth to seventh centuries AD. It connected most of the regions along the Mediterranean Sea. A couple of the researched sites in this thesis functioned as ports, like Classe or Aquileia, and were therefore directly connected to the maritime trade network. Even though shipwrecks with glass cargo are relatively uncommon, enough of them have been excavated to indicate the use of the maritime trade network in the dispersion of glass across the Mediterranean. Maritime trade was important for the shipment of the glass from the primary production places to the secondary production centres. Therefore, raw glass can be found on ships. However, already formed objects were also transported (Scott and Degryse 2014, 19).

In the research on maritime trade, two main hypotheses have been formed. One hypothesis states that maritime trade consisted of the direct shipping between major ports or emporia. The other hypothesis formulates the idea that the dominant pattern in antiquity was cabotage. This means that merchants were selling and buying some of their cargo in one harbour, after which they continued to other ports where they also sold part of their cargo and bought new trade goods, instead of selling their complete cargo in one place (Wilson 2011, 53). This hypothesis, which is indicated by the presence of mixed cargoes, is also confirmed by archaeological evidence. Excavations of shipwrecks show that mixed cargoes, as for example the presence of both amphorae and glass as found in the Iulia Felix wreck (Sylvestri *et al.* 2008, 331), were normal. However, this practice was probably also due to the efficient use of the space in the merchant ships.

The direct shipping theory is supported by the idea that it seemed more logical for merchants to know the route they were going to take, so they could match their cargo with the markets they were going to visit (Wilson 2011, 54). Otherwise the merchants would travel a long way without the certainty of even selling their goods. Therefore, trade goods might have been collected in the larger ports, which were located near production centres. After the collection, the merchandise was loaded onto a merchant ship that would travel across the Mediterranean Sea to another large port, where the goods were unloaded and sold. From there the trade ware was dispersed, either by smaller ships or over land, towards local markets. Moreover, mixed cargo could also be explained by the direct trade routes hypothesis, and not only by the cabotage theory. In order to supply overseas markets, a variety of trading goods was needed. These different goods could have been collected in one harbour at one side of the Mediterranean and then shipped in its entirety to another harbour at the other side of the sea.

The direct trade routes hypothesis is also supported by the presence of 'strong'/pure HIMT glass on a site. This indicates that HIMT glass was directly imported from its primary production centre because it did not have any opportunity to be recycled and mixed with other kinds of glass resulting in weak HIMT glass. North-Adriatic sites, like Classe and Aquileia show a large number of 'strong' HIMT glass (Maltoni *et al.* 2016, 11). This might indicate a direct connection between primary production sites in Egypt and some of the larger ports in Italy.

After the larger ships dropped their cargo at several emporia or larger ports, it was further dispersed by smaller ships along the coastline of Italy. This system took shape only after the collapse of the larger trade connections from the sixth century AD onwards (Wilson 2011, 52-53). This might be the explanation for why CaO-rich HIMT glass was so specifically dispersed along the Adriatic coast as Gliozzo *et al.* (2016, 106) states. The glass might have been imported in the larger trade centres like Aquileia, after which it was shipped along the coast to smaller settlements. Since the smaller ships only travelled short distances with their cargo, the CaO-rich HIMT glass would not get dispersed throughout the entire Italian peninsula and Sicily, but only near the larger ports like Aquileia.

A couple of the analysed sites in this thesis are directly connected to the sea transport network, like Piazza Bovio (Naples), Ganzirri, Domus of Tito Macro (Aquileia), Casa delle Bestie Ferite (Aquileia), Classe, and the Palatine Hill (Rome). The compositional groups of glass found at these sites can be compared to similar groups dating between the fourth to seventh centuries AD in Carthage, Cyprus, and Herdonia (Arletti *et al.* 2010, 110). The Italian sites, which were directly connected to the sea transport network, were important connection points between the larger Mediterranean network and the local markets in Italy itself (Gliozzo *et al*. 2016, 106-107). It is interesting to note that all these sites, except for Ganzirri, also show remains of secondary glass production at the site. Indicators for the presence of secondary glass production are working wastes, moils, (defected) fragments, test droplets, and raw chunks of glass. Some sites, like Piazza Bovio, Classe, and Catania, also yield remains of furnaces. Excavations at Catania even showed several fragments of metallic tools, which was very rare (De Francesco *et al.* 2014, 138; Di Bella *et al*. 2015, 354; Gliozzo *et al.* 2017, 710; Maltoni *et al.* 2015, 3). Especially the Palatine Hill (Rome), Classe, and the city of Aquileia are known as large glass centres which both served as production and consumption sites. This might indicate that the newly imported glass from the primary production places after arriving at the trade centres in Italy, were first formed into (new) objects before being traded throughout the country. The presence of a secondary workshop might therefore give the site an important role in the trade network, for its multifunctionality in the glass trade. It functions both as a node in the international glass trade, participating in the trade of raw glass, as well as in the local glass markets where the city is able to rework the raw glass into objects and fulfil the needs of the local customers.

Most of the ingots and unworked chunks of glass which are found in Italy seem to have consisted of raw glass which was imported directly from the primary production centres. However, seven out of the nine excavated ingots and unworked chunks of glass from the Palatine Hill (Rome) show signs of recycling or contamination of the raw glass. This is concluded from the heightened levels of copper (Cu) and antimony (Pb) (Gliozzo *et al.* 2017, 716-721). Whether the chunks of raw glass were made of recycled glass in Italy by mixing several different batches of used glass or were already recycled in the production centres in Egypt is not clear (Gliozzo *et al*. 2017, 724). This phenomenon has not been seen on the other sites yielding HIMT in their assemblage, which makes this situation interesting. The glass might have already been recycled in Egypt or in a different production centre in the trade network. This would suggest that the shipping of the glass would not always happen through a direct trade connection, but that there would be multiple stops along the way. Another explanation is that pure raw glass would arrive in Italy, after which it was partly used and then melted together with other batches of glass into a new ingot, resulting in a recycled ingot.

Figure 12: road map of Roman Italy (https://brewminate.com/).

4.2 Trade in Italy

After the introduction of HIMT glass in the trade network, around the fourth century AD, it slowly took over the glass market. HIMT glass was first shipped to larger ports across Italy. From there it was dispersed throughout Italy, by ships along the coast (cabotage), or via the large road system that was developed during the period of the Roman empire (fig. 12).

	HIMT glass Absolute amount	Percentage	**Non HIMT glass** Absolute amount	Percentage	**Total amount of objects (100%)**
Ganzirri	4	50%	4	50%	8
Galatea	11	84.6%	2	15.4%	13
Mevaniola	6	60%	4	40%	10
San Genesio	24	82.8%	5	17.2%	29
Piazza Bovio	5	27.7%	13	72.3%	18
Rocca di Asolo	8	21.1%	30	78.9%	38
Casa delle Bestie Ferite (Aquileia)	47	75.8%	15	24.2%	62
Domus of Tito Macro (Aquileia)	33	47.8%	36	52.2%	69
Catania	20	86.9%	3	13.1%	23
Palatine Hill	15	78.9%	4	21.1%	19
Faragola	16	50%	16	50%	32
Herdonia	26	56.5%	20	43.5%	46
Classe	51	89.5%	6	10.5%	57
St. Prosdocimus (tesserae)	44	45.8%	52	54.2%	96
San Giusto	14	40%	21	60%	35
Grado & Vicenza	45	75%	20	25%	65

Table 2: presence of HIMT glass (HIMT, HIMT 1, HIMT 2, CaO rich HIMT, CaO rich-Na2O poor HIMT, Groupe 1, Groupe 2, Série 2.1, Groupe 3, Série 3.2, RNCBGY 1/HIMT, HIMT/RNCBGY 1) versus non HIMT glass (the remainder of the glass groups).

HIMT glass became predominant at multiple sites in Italy, especially along the Adriatic coast (Cagno *et al.* 2012, 1544; Maltoni et al. 2015, 15). The composition of the glass assemblages at the sites yielding HIMT glass differs per site as can be seen in table 1 and 2. Something that needs to be considered when analysing the results of the research conducted for this thesis is that not the same amount of objects were analysed per site. Therefore, large differences in the percentual presence can be seen (table 2). For example, if you compare a group of eight objects with a group of 35 objects, the presence of four objects of one compositional group is already 50% in the group of four objects, while in the other group it is 11%. The smaller the group of analysed objects, the larger the influence of the separate objects will be on the percentage of the presence of a glass compositional group. However, even though the influence of the individual objects might differ per site, several explanations for the differences in composition per site will be given below in order to reconstruct the dispersion of HIMT glass compared to the other kinds of glass that are found on the same sites.

Ten out of 17 sites show a majority of HIMT glass compared to other types of glass. However, the variety of presence of HIMT glass on the sites does not seem to depend on the region. For example, the glass assemblages from Catania and Galatea (Sicily) show that their glass assemblage consists of around 85% of HIMT glass. Ganzirri, on the contrary, another site and one of the main ports of Sicily at the time, has a varied glass assemblage comprising both HIMT (four objects) and non-HIMT (four objects). At the sites which are all located in the same area in the mid-south of the peninsula, San Giusto, Herdonia and Faragola, there does not seem to be a convincing majority of HIMT. The most obvious division is 60% of non-HIMT glass over 40% of HIMT glass in San Giusto.

In the north of the Italian peninsula along the coast of the Adriatic Sea, there is also not a standard division for HIMT versus non-HIMT glass. At Classe, Grado, Vicenza and Casa delle Bestie Ferite (Aquileia), there is a large majority of HIMT glass. However, at Rocca di Asolo, Domus of Tito Macro and St. Prosdocimus, HIMT glass is the minority of the glass assemblage. It can be concluded that HIMT glass was not present in the same percentage on every site.

A possible explanation for the variation of the composition of the glass assemblages between the different sites can be the way of excavating, for only a part of the site is excavated or analysed. Moreover, the diversity of the composition of glass assemblages also depends on the variety of recycled glass used in secondary glassmaking (Cagno *et al.* 2012, 1544). This could result in a very broad diversity of glass groups or a very specific assemblage of glass when only one kind of glass is used for the secondary glass making. Another reason for the differences in composition of the glass assemblages might be because of the local demand for specific kinds of glass. These demands are reflected in the differences within the compositional groups present in the glass assemblages. The biggest difference can be seen in the presence of the Levantine I and

HIMT glass groups. Levantine I glass seems to be less recycled and therefore of higher quality than HIMT glass. As Nenna (2014, 186) describes, the quality of the technology, which was used to produce HIMT glass, was also much lower than the one used for Levantine glass. Furthermore, Egyptians used more recycled glass in the production of the primary batch to make the mixing of sand and the flux easier (Foy *et al.* 2003b, 46). Because of the lesser quality of the HIMT glass, it was also cheaper than Levantine glass. Both groups were therefore probably used for different purposes. Levantine glass might have served to make elite goods, because of its purity. HIMT glass, on the contrary, was cheaper and might therefore have been used to make common tableware. This kind of common glassware was sold on a different and probably larger market, for it was affordable for not only the rich people, but also the commoners (Gallo *et al.* 2014, 17). Therefore, depending on the local demand for specific glass goods, there might be a difference in the presence of several glass compositional groups per site. Furthermore, the presence of a specific glass group might give away some information about the functions of the glass that was used at that site.

The geographic location of the site might not only have had an impact on the composition of the entire glass assemblage, but also on the composition of the HIMT glass itself. HIMT glass was widely spread throughout Italy, but the specific CaO-rich HIMT glass was mostly found in the areas along the Adriatic Sea (Gliozzo *et al.* 2016, 132). This might indicate that the sites along the Adriatic Coast were tightly connected to each other. The reason why this kind of glass was only seen in this region and not dispersed throughout the entire peninsula is not completely clear. The presence of direct trade connections between the CaO-rich HIMT find places and its region of origin might also be a possible explanation. The rest of Italy might have been provided with other kinds of glass via different ports and trade routes. Another explanation might be that during the melting of the raw glass at secondary production centres along the Adriatic coast more calcium (Ca) was either intentionally or unintentionally added to the glass mixture.

4.3 Recycling

Recycling also took place in the fourth to seventh century AD in Italy, even though glass was still being imported and a reduction in the use of glass is seen in the western regions of the Mediterranean area from the mid-fourth century AD onwards. Paynter and Jackson (2016, 11) write that there seem to have been waves of import from Eastern and North African areas during the fourth/fifth centuries, the fifth/sixth and sixth/eighth centuries AD. These waves have been identified by their different compositions and lifespans. In between these waves, recycling practices were likely intensified. Because of these waves of import, new and old glass existed for some time together at the sites. When the import of new glass halted for a while, the present glasses were recycled and melted together, resulting in the mixing of different glass groups (Paynter and Jackson 2016, 11). Recycling was not only done on a large scale to meet the regular demand of the glass market, but also to fulfil the demand for specialized glasses like certain glass colours after the fourth century AD (Paynter and Jackson 2016, 14).

Presence of recycled glass	**Yes**	**No**
Ganzirri	X	
Galatea	X	
Mevaniola		X
San Genesio		X
Piazza Bovio	X	
Rocca di Asolo	X	
Casa delle Bestie Ferite (Aquileia)	X	
Domus of Tito Macro (Aquileia)		X
Catania		X
Palatine Hill	X	
Faragola	X (possibly)	
Herdonia	X	
Classe		X
St. Prosdocimus (tesserae)		X
San Giusto	X	
Grado & Vicenza		X

Table 3: presence of recycled glass at the sites.

Several of the analysed assemblages and sites show indications of recycling (table 3), which might have occurred on a small or larger scale. For example, at San Giusto, only a small amount of the glass objects shows signs of recycling, eight out of the 35 objects. At both Piazza Bovio and Herdonia recycling took place at the site itself, since they did not only function as secondary production centres, but probably also as recycling centres. This is indicated by crushed glass, processing waste, window sheets and mosaic remains (Francesco *et al.* 2014, 138). Almost all the recycled glass fragments show an Egyptian origin of the raw glass. According to Gliozzo *et al.* (2016), based on the idea that HIMT has an Egyptian origin, this might indicate that HIMT glass was the only glass that was used for recycling in the secondary production centres (Gliozzo *et al.* 2016, 106-107).

Casa delle Bestie Ferite, one of the sites in Aquileia, also yields information about recycling. The HIMT glasses from Casa delle Bestie Ferite are divided into weaker and stronger HIMT, from which the weaker HIMT group shows indications for recycling (Gallo *et al.* 2014, 15). The HIMT glasses at Theodoric's villa cannot be divided into strong and weak HIMT. However, in general, the levels of titanium (Ti), manganese (Mn) and iron (Fe) in the HIMT glasses on this site are distinctively lower than seen in other HIMT glass, and are comparable to the weaker HIMT group of Casa delle Bestie Ferite. According to Arletti *et al.* (2010), these low levels of titanium (Ti), manganese (Mn) and iron (Fe) can be ascribed to the recycling practice of regular Roman glass with HIMT glasses. A similar pattern is seen in Britain, researched by Foster and Jackson (2009). They state that when HIMT glass was introduced, it was first recycled with other types of glass, which resulted in weaker HIMT glasses. However, when a new wave of imported HIMT glass took over the market, weaker HIMT glasses got recycled with other HIMT glasses resulting in 'strong' HIMT glass (Gallo *et al.* 2014, 15).

It is not always clear why the assemblages show indications of recycling. Recycling might have been encouraged by the lack of enough new raw material. This might have been caused by the slowly diminishing maritime trade network around the sixth to seventh century AD. Causes that can be ascribed to this development are the Arab expansion during the seventh century AD, the invasion of Africa by the Vandals in the fifth century AD, or the Persian conquest of Alexandria in 617 AD, which also stopped the grain supply to the Byzantine empire. Additionally, the major imports from Rome halted, and also the ceramic evidence shows that African import declined heavily. In Rome, during the eighth century AD, ceramic finds indicate that the pottery was locally produced, which could have also been the case for glass products. Starting from the ninth century AD onwards, the trade grew slightly but was now focussed on mostly the western Mediterranean (Wilson 2011, 38-39). Since glass was often imported together with the ceramics from Eastern and North African regions, it can be concluded that the glass import also declined. To be able to fulfil the demand of the glass market in Italy, recycling might have started to play a larger role.

The exact period when recycling was discovered and fully used is still unsure, but literary sources suggest that recycling practices already existed since the first century AD (Duckworth 2020, 304). However, in what kind of form is still not clear, especially since coloured glass was not very practical for the recycling of glass since combining glass with different chemical properties might cause difficulties for the glass making process. Moreover, in order to recycle natron glass, a high temperature furnace technique was necessary and this was only achieved by the horizontal heating chambers which were used in a later period of time. However, recycling also had advantages, for example the reduction of production waste by using cullet for making new glass. This also explains why so little glass production is found in the glass workshops themselves (Degryse 2020, 288-289). Also, the way cullet improved the mixture of raw glass and the efficiency of volume input were very handy and might also have been the reason that the recycling of glass cullet not only was used with the recycling of glass but also during the production of primary raw material (Duckworth 2020, 306). Not only local glass waste was used in the production centres, glass cullet was also transported via the maritime trade network to other different secondary workshops to be melted into new objects. This is proved by the presence of a barrel filled with broken glass in the Iulia Felix shipwreck and the large amount of raw glass at the Embiez Ouest shipwreck (Degryse 2020, 289). Isotopic research has proven that these batches do not consist of a single batch of glass or come from one production unit, indicating that recycling happened at different places and therefore were probably small scale events (Degryse 2020, 294). Moreover, the cargo at the Iulia Felix shipwreck consisted of locally produced wares from North-Italy, showing that this ship was likely not intended for long-distance transport and confirming that the transport of cullet was likely to have happened over short distance trade routes. Also, the cullet was present in a small quantity and therefore not the main cargo of the ship (Duckworth 2020, 312-313).

In the case of an increasing amount of glass recycling combined with the fact that recycling were small scale happenings, the secondary production centres probably functioned as recycling centres before the glass was dispersed across the area. Moreover, the further away the workshops and consumers of the glass were from the primary production centres, the more likely it was that the glass had already been used and recycled (Paynter and Jackson 2016, 13). Therefore, it is not strange that the sites in Italy, which are almost on the other side of the Mediterranean, show signs of recycling in their glass assemblages. The presence of fresh glass on the Italian sites can be explained by the waves of import of fresh glass from the primary production centres, which also enforces the theory that Italy had direct connections with the primary production centres in the eastern Mediterranean area.

5. Conclusion

The aim of this study was to find out what the dispersion of HIMT glass looked like in the fourth to seventh century AD in Italy. To illustrate the presence of HIMT glass in Italy, 17 case studies have been examined. Every site was shortly described based on the location, date, the presence of several glass compositional groups and the characteristics of the glass assemblage. In the discussion, three main subjects, trade in the Mediterranean area, trade in Italy, and recycling have been discussed by means of the characteristics of the glass assemblages in order to answer the main research question: '*How is HIMT glass dispersed in Italy during the fourth to seventh centuries AD?*' The research question was subdivided into multiple sub-questions, which will be answered in the paragraphs below before answering the main research question.

The first sub-questions that were posed were: 'W*hat does the chemical composition of ancient glass dating between the fourth to seventh century AD look like? How do we recognize the several glass groups including HIMT glass?'* As can be concluded, the glass objects found in the assemblages dating to this period in Italy consisted of the base ingredients: silica, soda, and lime, with natron as flux. The glass assemblages did not consist of only one large glass compositional group but could be divided into multiple smaller compositional groups. The glass assemblages of 17 sites in Italy have been examined and many different glass groups can be distinguished based on the presence of different chemical elements and isotopes. The most common glass compositional groups are HIMT, Levantine glass, and Egyptian glass. The HIMT glass is distinguished by heightened levels of iron (Fe), manganese (Mn), and titanium (Ti). The subgroups of HIMT glass can be separated by looking at the differences in the heightened levels of iron (Fe), manganese (Mn), and titanium (Ti). HIMT glass seems to have a strontium (Sr) ratio between 0.7075 and 0.7090 indicating the use of inland lime sources instead of shells. The Levantine glass can be divided into two subgroups: Levantine I and Levantine II. Both Levantine glass groups have a higher strontium (Sr) ratio, close to 0.7092. This indicates the use of coastal lime sources, for example seashells. However, the lime (CaO) and soda contents in Levantine I glass are higher than the ones in Levantine II glass. The levels of silica (SiO_2) and alumina (Al_2O_3) are lower in Levantine I glass than they are in Levantine II glass. Egypt I and II glass are both similar in the high contents of alumina (Al_2O_3) and titanium oxide (TiO_2). Egypt I is furthermore known for its high magnesia (Mg) and low lime (CaO), while Egypt II is known for its high lime (CaO) content. The strontium (Sr) level is just like HIMT glass lower than can be found in Levantine glass, also implying the use of inland lime sources.

The second and third sub-questions are: '*How can we distinguish glass assemblages originating from either consumption or production sites? And how can we explain the role of secondary production centres in the trade network?'* The assemblages of both consumption and production sites contain the remains of a large variety of glass objects. However, a distinction can be made between the two different kinds of sites. Production sites yield the remains of finished glass objects as well as production waste. This includes cullets, test drops and melting waste. Next to the glass indicators for production, the remains of a furnace, fuel ash slag, charcoal, burned patches and tools, and at Catania even metal instruments have been found. Interestingly, the production sites included in this thesis are all located near the coast, both on the west and east side of Italy. However, this does not have to be the case everywhere, even though it can be convenient for the import of new glass. Mostly newly produced raw glass was shipped around the Mediterranean in large blocks. These had to be formed into vessels or other glass objects of use. Therefore, the glass had to be reformed locally, which is where the secondary production centres were used for. If the production sites were on the coast, the raw glass could be formed into vessels or other useful forms directly when it arrived in Italy and before being shipped throughout the whole country. This way, the glass could be shaped into the locally preferred shapes and accommodate the local demand. The secondary production centre would therefore not only have a production role but also a commercial role.

What needs to be considered is that the production centres which are being discussed in this thesis are the ones containing HIMT glass, and the ones that are known to contain HIMT glass on site. There might have been other production centres with or without HIMT glass which are located elsewhere, for example, more in the centre of Italy. This would also be understandable as Italy is a large country, and the transport of already formed vessels is more difficult than the transport of blocks of raw glass. To be able to fulfil the demand of glass in the centre or non-coastal areas in Italy, the raw glass might have been transformed into objects of use more inland.

'How can we explain the differences in composition of the glass assemblages and HIMT glass per site?' is the fourth sub-question of this research. The differences in

composition of the glass assemblages between different sites can be ascribed to the different availability of glass. Not all the sites were located close to trade routes, trade centres and/or secondary production centres. They therefore relied on the glass that was already present. Moreover, when the HIMT glass or other new kinds of glass would reach these sites, they would not immediately take over the glass assemblages. These new kinds of glass would come in at a slow pace and could exist next to the earlier kinds of glass. These differences cannot only be accounted for by the availability of glass, but also by the fact that different types of glass were used for different purposes. HIMT glass was cheaper and produced faster, which resulted in lower quality but it was often used for commonly used objects. Levantine glass, on the contrary, was more costly because of its high quality. It was therefore used for other and more highly-rated objects which were less commonly used.

The last sub-question is: 'W*hat role does recycling play in the life cycle of HIMT glass?'* As became clear after doing research, nine out of the 17 sites contain objects which show signs of recycling. However, not all the sites contain the same amount of objects with signs of recycling. This could have had many reasons. One of them is that the import of glass was not always steady between the fourth and seventh century AD. This resulted in an increasing level of reusing and recycling of the glass that was already present at the Italian peninsula. This process of recycling and remelting resulted in the presence of many different glass groups. During this process, HIMT glass was recycled together with roman glass resulting in weak HIMT glass. When later on, weak HIMT glass was mixed with new HIMT glass, strong HIMT glass was created. So the amount of recycled glass also depended on the number of already present glass on the site and therefore the need for the recycling practices differed per site.

Almost all the recycled glass fragments that have been researched, have an Egyptian origin. Because HIMT appears to have an Egyptian origin, the conclusion can be drawn that HIMT glass was the primary glass used for recycling in secondary production centres. Also because both Egypt I and II glasses were rarely found outside of Egypt, so these glass groups could not be the Egyptian glass used for recycling outside of Egypt. Moreover, it would be more logical if they used HIMT glass for recycling, because it had lower value than Levantine glass. Therefore, it would be less costly and less valuable to use this kind of glass for recycling. Furthermore, HIMT glass was produced on the other side of the Mediterranean. It is known that the further away the workshops and consumers of the glass were from the primary production centres, the more recycling had taken place before the glass would be at its ‘final destination’. This makes it more logical to find signs of recycling in the glass assemblages of Italy. Next to the recycled objects, there are also pure objects without signs of contamination or recycling. This can be explained by the waves of import of fresh glass, indicating a direct relationship between Italy and the primary production centres. What should be taken into account is that sometimes recycling is not recognized, when for example two similar compositional groups are mixed together. The amount of recycled glass recognized in an assemblage is therefore among others always the minimal estimate.

By providing information about the chemical composition of glass, the production of several glass compositional groups, recycling of glass and the dispersion of sites containing HIMT glass throughout the Italian peninsula, the following can be concluded in response to the main question: ‘*What does the dispersion of HIMT glass look like in Italy during the fourth to seventh centuries AD?’* During the fourth to seventh centuries AD, HIMT glass was imported into Italy from probably Egypt via various ports and secondary production centres in Italy. From here it was transported to other sites throughout the entire peninsula, where it was used for common ware. HIMT glass was not expensive, for it was made in a lower quality than other glass groups, like Levantine glass. This is one of the reasons that HIMT glass was recycled often. Next to the fact that it had a lower quality than other glass compositional groups, the import of glass was not always stable and the demand of glass was still large. This is also the reason why HIMT glass exists in weak and strong versions. The weak version of HIMT has been recycled often and was mixed with other types of glass. Strong HIMT glasses were HIMT glass mixed with other HIMT glass resulting in even higher levels of iron (Fe), manganese (Mn), and titanium (Ti).

For further research, the information of this thesis could be extended with yet unpublished assemblages containing HIMT glass and located on the Italian peninsula. These publications might yield more specific information about the composition of new assemblages, or elaborate on already known geographical dispersion of HIMT glass in Italy. Especially since research on the chemical composition of glass is still being increased and improved. Another interesting research topic would be the local shapes of HIMT glass. HIMT glass was imported into Italy in blocks of raw glass, after which it was shaped at local production centres. It would be interesting to see if the shapes of the glasses therefore can be distinguished based on local styles. Also, in this research the sole focus was on the dispersion of HIMT within the Italian peninsula, even though HIMT glass was also found in other parts of the Mediterranean. The combination of data from other countries with the overview of the dispersion in Italy might bring interesting insights into the general dispersion of HIMT glass. This thesis tried to combine the chemical elements of the different glass compositional groups with the social developments during the fourth to seventh centuries AD. Because this thesis was not primarily focused on chemical research, only the useful elements for this specific research have been considered. There could be more interesting additional information in the remaining unused data retrieved from these glass assemblages. In a more specific research on the chemical composition of glass, this part of the research can probably be extended further to reconstruct the dispersion patterns of HIMT glass even more precisely.

6. Abstract

Since the 1960s, research on the chemical composition of ancient archaeological glass has been executed. It has become clear that raw ancient glass exists of three main ingredients: silica, lime, and a flux. Next to these ingredients, iron is always found in the mix which gives glass naturally a green or blue colour. Around the fourth century AD, a new type of glass was introduced. This glass type was probably made in Egypt and is distinguishable from the other compositional types of glass by its yellow to green colour. Research indicates that the glass has high levels of iron (Fe), manganese (Mn), and titanium (Ti) in its composition. This is why, in 1994, the term 'HIMT' glass is introduced by prof. I. Freestone.

This research focuses on the dispersion of HIMT glass during the fourth to seventh centuries AD on the Italian peninsula to fill in gaps in the knowledge of the general dispersion of HIMT glass throughout the Mediterranean area. HIMT glass was not the only type of glass on the market. In this research, the focus lies on HIMT glass, but to provide more context about the general glass market, also other types of glass like Egypt I and II and Levantine glass are being discussed. It is generally accepted that there are two primary glass production areas for all the ancient glass: the Levant and Egypt. The glass was formed here into large chunks which were shipped throughout the Mediterranean area to secondary production areas. There the glass was formed into vessels or other useable objects. To understand where the glass originates, chemical research is performed. Hereby, not only the chemical elements, which could be added intentionally or unintentionally, are taken into account, also isotopes, like neodymium (Nd) and strontium (Sr) which respectively indicate the age of the sediments and the source of lime, are being researched. This results in the distinction of several glass compositional groups.

This research aims to answer the following question: 'How is HIMT glass dispersed in Italy during the fourth to seventh centuries AD?'. After providing information on the chemical composition of glass and the existing glass compositional groups, an overview is given of 17 sites on the Italian peninsula where HIMT glass is present in the glass assemblage. These sites are researched using archaeological publications. A distinction is made between production sites, where the glass was formed into objects and where production waste was found, and consumption sites, where the objects were solely

used. Looking at the context of the sites and the composition of the glass assemblages found there, an overview of the presence of HIMT glass on the Italian peninsula could be provided. To understand the specific dispersion of the glass, three main subjects, trade in the Mediterranean area, trade in Italy, and recycling practices are researched. The research concludes that the glass was shipped from Egypt into Italy via multiple ports and trade routes after which the glass was spread throughout Italy. HIMT glass was mostly used for common ware, because of its relatively low quality, and therefore also useful for recycling.

Since this research is based on the existing publications of sites containing HIMT glass, future research could include looking at yet unpublished sites, the data from already published assemblages that have not been used for this thesis, and the possibility of regional differences in shapes of HIMT glass.

List of tables

List of figures

Internet pages

https://www.cmog.org/article/mystery-slab-beth-shearim , accessed on 5 January 2022.

https://transportgeography.org/contents/chapter1/emergence-of-mechanized-transportation-systems/roman-empire-c125ce , accessed on 5 January 2022.

https://brewminate.com/an-ancient-network-the-roads-of-rome , accessed on 5 January 2022.

References

Arletti, R., C. Giacobbe, S. Quartieri, G. Sabatino, G. Tigano, M. Triscari and G. Vezzalini, 2010. Archaeometrical investigation of Sicilian Early Byzantine glass: Chemical and Spectroscopic data. *Archaeometry* 51 (1), 99-114.

Arletti, R., G. Vezzalini, S. Benati, L. Mazzeo Saracino and A. Gamberini, 2010. Roman Window glass: a comparison of finding from three different Italian sites. *Archaeometry* 52 (2), 252-271.

Ayache, M., J-C. Dutay, T. Arsouze, S. Révillon, J. Beuvieur and C. Jeandel, 2016. High-resolution neodymium characterization along the Mediterranean margins and modelling of εNd distribution in the Mediterranean basis. *Biogeosciences* 13, 5259-5276. doi:10.5194/bg-13-5259-2016

Bowersock, G.W., P. Brown and O. Grabar, 1999. *Late Antiquity: A guide to the Postclassical World*. Harvard: President and Fellows of Harvard College.

Brems, D. and P. Degryse, 2013. Trace Element Analysis in Provenancing Roman glass-making. *Archaeometry* 56 (S1), 1-21. Doi: 10.1111/arcm.12063

Brems, D., M. Ganio and P. Degryse, 2014. The Sr-Nd isotopic fingerprint of sand raw materials, in P. Degryse, *Glassmaking in the Greco-Roman world*. Leuven: Leuven University, 51-68.

Brill, R. H., 1969. The scientific investigation of ancient glasses. *In Proceedings of the 8th International Congress on Glass*, London 1968, 47–68. Sheffield, Society of Glass Technology.

Bugoi, R., C-G Alexandrescu and A. Panaite, 2018. Chemical composition characterization of ancient glass finds from Troesmis – Turcoaia, Romania. *Archaeological Anthropological Science 10*, 571-586. DOI 10.1007/s12520-016-0372-6

Cagno, S., L. Favaretto, M. Mender, A. Izmer, F. Vanhaecke and K. Janssens, 2012. Evidence of early medieval soda ash in the archaeological site of San Genesio (Tuscany). *Journal of Archaeological Science* 39, 1540-1552.

Ceglia, A., P. Cosyns, K. Nys, H. Terrynn, H. Theinpont and W. Meulebroeck, 2015. Late antique glass distribution and consumption in Cyprus: a chemical study. *Journal of Archaeological Science* 61, 213-222. https://doi.org/10.1016/j.jas.2015.06.009

D.E. Eicholz, Pliny – Natural History Books 36-37 (Loeb, Harvard, 1962).

De Francesco, A.M., R. Scarpelli, F. Del Vecchio and D. Giampaola, 2014. Analysis of Early Medieval glass from excavations at 'Piazza Bovio', Naples. *Archaeometry* 56 (1), 137-147.

De Juan Ares, J., N. Schibille, J. Molina Vidal and M.D. Sanchez de Prado, 2019. The Supply of Glass at Portus Ilicitanus (Alicante, Spain): A meta-analysis of HIMT glasses. *Archaeometry* 61 (3), 647-662. Doi: 10.1111/arcm.12446

Degryse P., R.B. Scott and D. Brems, 2014. The archaeometry of ancient glassmaking: reconstructing ancient technology and the trade of raw materials. *Antiquité* 2, 224-238. Doi: 10.4000/perspective.5617

Degryse, P., M. Ganio, S. Boyen, A. Blomme, B. Scott, D. Brems, M. Carremans, J. Honigs, T. Fenn, and F. Cattin, 2014. Primary glass factories around the Mediterranean, in P. Degryse, *Glassmaking in the Greco-Roman world*. Leuven: Leuven University Press, 97-112.

Degryse, P., and A.J. Shortland, 2020. Interpreting elements and isotopes in glass: a review. *Archaeometry* 62 (1), 1-17. Doi: 10.1111/arcm.12531

Degryse, P., and 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, 1993-2000. Doi: 10.1016/j.jas.2008.01.002

Degryse, P., 2020. Elements, Isotopes, and Glass Recycling, in C.N. Duckworth and A. Wilson, *Recycling and Reuse in the Roman Economy*. Oxford: Oxford University Press, 285-300.

Devulder, V. and P. Degryse 2014. The sources of Natron, in P. Degryse, *Glassmaking in the Greco-Roman world*. Leuven: Leuven University Press, 87-96.

Devulder, V., F. Vanhaecke, A. Shortland, D. Mattingly, C. Jackson and P. Degryse, 2014. Boron Isotopic composition as provenance indicator for the flux raw material in Roman natron glass. *Journal of Archaeological Science* 46, 107-113. DOI: http://dx.doi.org/10.1016/j.jas.2014.03.009

Di Bella, M., C. Giacobbe, S. Quartieri, G. Sabatino and U. Spigo, 2015. Archaeometric characterization of Proto-Byzantine glass workshop from the Roman amphitheatre of Catania (Sicily, Italy). *European Journal of Mineralogy* 27 (3), 353-363. DOI: 10.1127/ejm/2015/0027-2449

Duckworth, C. N., 2020. Seeking the Invisible: New Approaches to Roman Glass Recycling, in C. N. Duckworth and A. Wilson (eds), *Recycling and Reuse in the Roman Economy.* Oxford: Oxford University Press, 301-356.

Fiori, C. and M. Vantini, 2004. Chemical Composition of Glass and its Raw Materials; Chronological and geographical Development in the First Millennium AD, in M. Beretta*, When Glass matters. Studies in the history of science and art from Graeco-Roman Antiquity to early modern Era.* Florence: Casa Editrice Leo S. Olschki.

Foster, H. and C. 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* 26, 199-204. doi:10.1016/j.jas.2008.08.008

Freestone, I. C., 1994. Appendix: chemical analysis of 'raw' glass fragments, in H.R. Hurst, *Excavations at Carthage: the British mission. Volume II, 1. The circular harbour, north side. The site and finds other than pottery*. Oxford: Oxford University Press.

Freestone, I., Y. Gorin-Rosen and M.J. Hughes, 2000. Primary glass from Israel and the Production of Glass in Late Antiquity, in: *La route du verre. Ateliers primaires et secondaires du second millénair av. J.-C. au Moyen Âge.* Colloque organise en 1989 par l'Association française pour l'Archéologie du Verre (AFAV) Lyon: Maison de l'Orient et de la Méditerranée Jean Pouilloux, 65-83, (Travaux de la Maison de l'Orient Méditerranéen, 33).

Freestone, I.C., P. Degryse, J. Lankton, B. Gratuze and J. Schneider, 2018. HIMT, glass composition and commodity branding in the primary glass industry, in P. Degryse, *Things that travelled. Mediterranean glass in the first millennium CE*. London: UCL Press, 159-190.

Freestone, I.C., R.E. Jackson-Tal, I. Taxel and O. Tal, 2015. Glass production at an Early Islamic workshop in Tel Aviv. *JAS*62, 45-54.

Gallo, F. and A. Silvestri, 2012. Medieval Glass from Rocca di Asolo (Northern Italy): An archaeometric study. *Archaeometry* 54 (6), 1023-1039.

Gallo, F., A. Marcante, A. Silvestri and G. Molin, 2014. The glass of the "Casa delle Bestie Ferite": a first systematic archaeometric study on Late Roman vessels from Aquileia. *Journal of Archaeological Science* 41, 7-20.

Geilmann, W., 1955. Beiträge zur Kenntnis alter Gläser III. Die chemische Zusammensetzung einiger alter Gläser, insbesondere deutscher Gläser des 10. bis 18. Jahrhunderts. *Glastechnische Berichte* 28, 146–156.

Gliozzo, E., B. Lepri, L. Saguì and I. Memmi, 2017. Glass ingots, raw chunks, glass wastes and vessels from 5th century AD Palatine Hill (Rome, Italy). *Archaeological Anthropological Science* 9 (5), 709-725.

Gliozzo, E., E. Braschi, F. Gianetti, A. Lagone and M. Turchiano, 2019. New geochemical and isotopic insights into the Late Antique Apulian glass and the HIMT1 and HIMT 2 productions – the glass vessels from San Giusto (Foggia, Italy) and the diagrams for provenance studies. *Archaeological Anthropological Science* 11, 141-170. DOI 10.1007/s12520-017-0531-4

Gliozzo, E., M. Turchiano, F. Giannetti and A. Santagostino Barbone, 2016. Late Antique glass vessels and production indicators from the town of Herdonia (Foggia, Italy): New data on CaO-rich/weak HIMT glass. *Archaeometry* 58 (1), 81-112. doi: 10.1111/arcm.12219

Gliozzo, E., M. Turchiano, F. Giannetti and I. Memmi, 2016. Late Antique and Early Medieval Glass vessels from Faragola (Italy). *Archaeometry* 58, 113-147. doi: 10.1111/arcm.12242

Gratuze, B. and J.N. Barrandon, 1990. Islamic glass weights and stamps: analysis using nuclear techniques. *Archaeometry* 32 (2), 155-162.

Henderson, J., 1985. The raw materials of early glass production. *Oxford Journal of Archaeology* 4 (3), 267, 291. https://doi.org/10.1111/j.1468-0092.1985.tb00248.x

Henderson, J., 2013. A*ncient Glass: An Interdisciplinary Exploration.* Cambridge: Cambridge University Press. DOI: https://doi.org/10.1017/CBO9781139021883.005

Jackson, C. and H. Foster, 2015. Provenance studies and Roman glasses, in J. Bayley, I. Freestone and C. Jackson, *Glass of the Roman World.* Oxford: Oxbow Books, 44-56.

Maltoni, S., A. Silvestri, A. Marcante and G. Molin, 2016. The transition from Roman to Late Antique glass: new insights from the Domus of Tito Macro in Aquileia (Italy). *Journal of Archaeological Science* 73, 1-16.

Maltoni, S., T. Chinni, M. Vandini, E. Cirelli, A. Silvestri and G. Molin, 2015. Archaeological and archaeometric study of the glass finds from the ancient harbour of Classe (Ravenna-Italy): new evidence. *Heritage Science (*3) 13, 1-19. DOI 10.1186/s40494-015-0034-5

Mirti, P., A. Casoli, and L. Appolonia, 1993. Scientific analysis of Roman glass from Augusta Praetoria. *Archaeometry 35*, 225–240.

Nenna, M.D., 2014. Egyptian glass abroad: HIMT glass and its markets, in D. Keller, J. Price and C.M. Jackson, *Neighbours and successors of Rome: traditions of glass production and use in Europe and the Middle East in the later 1st Millennium AD.* Oxford: Oxbow books, 177–193.

Phelps, M., I.C. Freestone, Y. Gorin-Rosen and 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. http://dx.doi.org/10.1016/j.jas.2016.08.006

Paynter, S., 2006. Analyses of colourless Roman glass from Binchester, County Durham. *Journal of Archaeological Science* 33, 1037-1057. doi:10.1016/j.jas.2005.10.024

Paynter, S. and C. M. Jackson, 2016. Re-used Roman rubbish: a thousand years of recycling glass. *Post-Classical Archaeologies* 6, 31-52.

Rehren, Th, and I.C. Freestone, 2015. Ancient glass: from kaleidoscope to crystal ball. *Journal of Archaeological Science* 56, 233-241. DOI: http://dx.doi.org/10.1016/j.jas.2015.02.021

Sayre, E. V. and R. W. Smith, 1961. Compositional categories of ancient glass. *Science* 133, 1824–1826.

Scott, R.B. and P. Degryse, 2014. Archaeology and archaeometry of natron glass making, in P. Degryse, *Glassmaking in the Greco-Roman world*. Leuven: Leuven University Press, 15-26.

Scott, B., B. Neyt, D. Brems, K. Eekelers, A. Shortland, and P. Degryse, 2017. Experimental mixing of natron and plant ash style glass: implications for ancient glass recycling. *European Journal of Glass Science and Technology A, Glass technology* 58 (1), 8-16.

Schibille, N., A. Sterrett-Krauwe and I.C. Freestone, 2017. Glass groups, glass supply and recycling in Late Roman Carthage. *Archaeological Anthropological Science* 9, 1223-1241. DOI 10.1007/s12520-016-0316-1

Schibille, N., B. Gratuze, E. Olliver and É. Blondeau, 2019. Chronology of early Islamic glass compositions from Egypt. *Journal of Archaeological Science* 104, 10-18. https://doi.org/10.1016/j.jas.2019.02.001

Silvestri, A., G. Molin and G. Salviulo, 2005. Roman and Medieval glass from the Italian area: bulk characterization and relationships with production technologies. *Archaeometry* 47(4), 797-816.

Silvestri, A., G. Molin and G. Salviulo, 2008. The colourless glass of Iulia Felix. *Journal of Archaeological Science* 35, 331-341. doi:10.1016/j.jas.2007.03.010

Silvestri, A., S. Tonietto and G. Molin, 2011. The paleao-Christian glass mosaic of St. Prosdocimus (Padova, Italy): archaeometric characterisation of 'gold' tesserae. *Journal of Archaeological Science* 38, 3401-3414. doi:10.1016/j.jas.2011.07.027

Strabo Geography 17.1.23, Pliny NH 31.46

Turner, W. E. S., 1956. Studies in ancient glasses and glassmaking processes. Part IV. The chemical composition of Ancient Glasses. *Journal of the Society for Glass Technology* 40, 162–186.

Verità, M., 1995. Le analisi di vetri, in D. Foy (ed.) *Le verre de l'antiquité tardive et du haut moyen âge. Typologie, chronologie, diffusion*, 291–300. Guiry-en-Vexin, Musée archéologique départemental du Val-d'Oise.

Wilson, A., 2011. Developments in Mediterranean shipping and maritime trade from the Hellenistic period to AD 1000, in D. Robinson and A. Wilson. *Maritime Archaeology and Ancient Trade in the Mediterranean*. Oxford: Oxford Centre for Maritime Archaeology, 33-60.

Internet pages

https://www.britannica.com/science/chromophore , accessed on 5 January 2022.