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A combined chemical and lead isotope analysis of Roman glass from Sagalassos (south-west Turkey)

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Figures cover: overview Sagalassos: http://tursaga.com and glass: after B. Van der Meulen and D. Veys, Burdur Museum Collection (http://tursaga.com).

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Table of Contents

Preface

This research is performed as final part of the requirements to obtain a master's degree in Archaeology at Leiden University. For me, the subject of this thesis was not only challenging and educational, it also was outside my comfort zone. By reading lots of literature about the subject and obtaining the necessary knowledge I was able to bring the analyses and this research to a success. The guidance of my supervisor, Patrick Degryse, was of great help in gaining this success, for which I am very thankful. Because of his fieldwork in Sagalassos and work at the University of Leuven he has a far going knowledge of the site. I would also like to thank Tania Timmer and Ronald Jong who were always there for advice and support.

Enschede, 12th of September.

1. Introduction

This thesis and research is written and carried out in the context of graduating for the master study Archaeology at the University of Leiden. It concerns the combined analysis of chemical and lead isotopic data of Roman glass samples. By combining the two analysing techniques, a new approach for interpreting data is used. An approach that already proved to be effective for interpreting data of metal objects and is now tested on a different material, glass. In order to make the interpretations, extensive data analysis was carried out, which is the main method in this research. The research did not always go as planned, because some parts took great effort to complete. However, it also was a challenging and educational project. The 243 glass samples that were used for this research have been found during excavations in Sagalassos, an ancient city situated in the Taurus Mountain chain in south-west Turkey. This city was mainly abandoned in the 7th century AD (Waelkens 2002), to then disappear completely in the 13th century (Waelkens *et al.* 2011). Extensive excavations began in 1990 led by M. Waelkens from the University of Leuven, which put Sagalassos back on the map.

1.1 Research problem

FLAME (Flow of Ancient Metals across Eurasia) is a project that has developed a method to map the flow of Bronze Age metal through Eurasia (http://flame.arch.ox.ac.uk). It is argued that the conventional model to provenance copper alloys is incorrect, as it does not take the effects of complex human actions on the material composition and the period of time in which an object moves from its source to archaeological deposition into account. Therefore, chemical and isotopic data are sometimes wrong in assigning objects to a specific source. Subsequently, this often leads to a mismatch with other archaeological data. FLAME proposes an approach that outlines the dynamic nature of metal in circulation. Rather than a precise provenance, this method determines the timing and origin of new input of (fresh) materials into the system.

However, metal is not the only material for which this provenance assignment is difficult. The chemical and isotopic composition of glass is also frequently influenced by human actions in the past, such as mixing materials from different sources, recycling or glass-working (secondary production). One would argue that it is possible to create a similar system as FLAME has, wherein the flow of glass is characterised. The challenge is then to adjust the existing method, for mapping the metal flow, to glass, and to test if this approach is successful or even possible to apply.

1.2 Research objectives

The aim of this research is to test a new method of interpretation, similar to the method that was used to map the flow of metal in the Bronze Age (project FLAME). The goal is to test in which manner and extent the method will be successful in looking at glass materials from one context. In this way, a contribution to setting up a possible new research method for glass materials can be made.

1.3 Research questions

The main research question is as follows: Is the proposed method for interpretation, according to the approach in Pollard and Bray (2015), with elemental and isotopic data suitable for mapping ‘the flow of glass’ of glass assemblages from Sagalassos (south-west Turkey) dating from 1-675 AD?

Mapping ‘the flow of glass’ of the glass assemblages from Sagalassos comprises:

1. How can the changing nature of the chemical and lead isotope composition of the glass assemblages from Sagalassos be interpreted? What are the striking changes and similarities between the ‘fingerprints’ of the glass assemblages from the subsequent time periods?
2. Is it possible and to what extent, to identify the timing and general origin of new inputs of glass into the system of the assemblages from Sagalassos?
3. Is it possible to interpret such changes in a social-geographical context?

1.4 Relevance

The importance of this research can be divided into two main aspects. The benefits of the information that are obtained about the glass samples from Sagalassos and those about testing a new method for interpreting chemical and lead isotope data. With the first aspect, new knowledge and insights about the glass samples from Sagalassos are obtained, which is an addition to the current knowledge about the site and its material culture. The information can be used to study things like the material composition of glass through time, glass production, glass recycling and mixing, provenance of raw materials and trade routes. What is more, all this information can be of help in creating insight in the development of the material culture of glass in this time period. Additionally, it can also contribute to more specific future research about the site Sagalassos, as it can be used as a source of information. All this information and its possible uses are relevant for the archaeological research team of the University of Leuven and all the organisations and institutions that are related to the excavations of this university or the site itself. Some of these organisations are located in Turkey and indicate the local importance of this research. Such as, interest of the local population in their history or the use of information in museums or at the site to inform tourists.

The second aspect demonstrates the broader scientific significance of this research, for archaeological research in general. By testing a new method, information can be gathered about if it works or not, if it yields more information than research performed by the current approach and if its execution is doable. Furthermore, trying out new approaches and methods keeps science moving and focused. If this new approach for interpreting data works, this research will have contributed to introducing a new range of research options for doing glass analysis. Lastly, a short personal motivation will clarify why this subject and research is relevant to the researcher itself. The researcher wanted to study something new in order to broaden the knowledge she would have when graduating and to add some new ability to her current education. As there was an interest in research related to archaeological glass and metal and curiosity after chemical analysis, this became the subject.

1.5 Related research

There is no previous done research that is similar to this research, focused on the material glass. As this study represents a new approach for data interpretation, it was not expected that this kind of research would be available. However, similar research has been done for metal finds and proved to be very successful. In fact, the proposed method for interpretation in this research derives from the same approach that is applied to metal finds and which is developed by project FLAME (http://flame.arch.ox.ac.uk). This project has published several articles in which the approach is discussed and which are useful for setting up a similar approach in this research (like, Bray and Pollard 2012; Bray *et al.* 2015; Pollard and Bray 2015). Also, examples of other combined research might be of help in building up this research, like using a combination of lead and strontium isotopic ratios for analysing glass samples (Degryse *et al.* 2006). Furthermore, literature about glass finds in Sagalassos and the site itself will be useful for creating an overview of the archaeological background. Lastly, previous performed laboratory research provides the needed chemical and lead isotope data for this research.

1.6 Thesis structure

After this introduction chapter and the methodology the archaeological background is considered in order to provide a theoretical framework. After this the results are presented, which are interpreted and discussed in chapter 5 ‘data analysis and discussion’. That chapter is divided in a provenance, recycling, lead isotope and combined analysis. The discussion continues and the research questions are answered in chapter 6 ‘conclusion’.

2. Methodology

In this chapter the used methodology is discussed in order to make this research reliable and verifiable. An explanation is given about how the data has been used to answer the research questions. First the main method, data collection, data characteristics, the research process and the manner of the analyses are considered in section 2.1, followed by the sampling and in short the analytical procedure in sections 2.2 and 2.3.

2.1 Data analysis

This research is both qualitative and quantitative, in which chemical element and lead isotope ratio data are re-examined together with artefact context and chronology in order to create and discuss the history of a glass assemblage on a site level. The main method is data analysis. The multiple analyses that are made in this research are based on already known and partly interpreted data. The known data is used to make new and additional interpretations in this research by organizing, classifying and interpreting it in a different way.

The data that is interpreted in this research is collected through analysis, available Excel documents and literature research. All the samples used in this research are a collection of data from previous done studies, no new samples were obtained especially for this research. Chemical and lead isotope data acquired through laboratory work and used for other studies was gathered from publications in literature and overviews in Excel documents provided by P. Degryse from the University of Leuven and Leiden. From all these datasets, two databases have been made in Excel to use in this research (appendix 3). One is a collection of all the sample data in general and classified in time periods. The second is smaller, more detailed and only contains the samples for which the lead isotope ratios are known. Literature was mainly collected through the internet, where online published articles from scientific magazines are available.

The literature that has been studied concerns subjects like chemical (trace) elements, isotopic Pb, Sr and Nd research and composition, glass composition, general information about the material and production of (primary) glass, the site Sagalassos and its structures and finds, Roman lead sources in the Mediterrenean, primary glass provenances and the concept of flow. The chemical and isotopic data are, as mentioned above, organized in databases in Excel documents, with 14 to 47 different information fields in each database (appendix 3). In it, the data is classified, sometimes in several Excel sheets, in time period, glass colour, provenance, recycling and samples for which both lead isotope ratios and the chemical lead content are known. These categories are based on criteria that are explained into detail in chapter 5 ‘Data analysis and discussion’. For example, the criteria and threshold values to determine the provenance of samples are discussed in section 5.1.1 and table 5.2 and the criteria to indicate recycling are discussed in section 5.2.1.

The two databases were made by combining data of all known natron glass samples with chemical and/or lead isotope ratio measurements/calculations from Sagalassos dating from 1-700 AD. Next, a framework of criteria based on literature was set up in order to divide the data into different categories. These were used to make detailed analyses, tables and diagrams of the data in Excel and Word, from which interpretations and conclusions could be made. The analyses were made by comparing the data in each group and that of the different groups with each other to indicate notable differences and similarities in the data. To connect the data with a wider context, it was also used to make comparisons with data from literature. For example, an overview has been made of the lead isotope ratios of several geographical different areas that can be used as a comparable reference source for the lead isotope ratios of the samples from Sagalassos.

An adaption on the method discussed in Pollard and Bray (2015), to indicate the flow of metal, has been used as a framework to set up the method for this research. Since the method described in that article if focused on metal and not on glass some alternations were necessary in order to use it in this research. Similar as in the article, the flow of glass is characterized by using a data-led approach and the reinterpretation of existing data. By analysing chemical and isotopic data of a glass assemblage, snapshots of flow can be compared with each other and put into context. The interpretation of the chemical composition is described as a two-stage process by Pollard and Bray (2015). With bronze, major and trace element analysis can be used to indicate the alloy composition and to determine preliminary copper groups. The first step in this process is a presence/absence classification for the most common main and trace elements (e.g. Sn, Pb, Zn, As, Sb, Ag and Ni). A trace element is present when its concentration is higher than 0.1% and a major element needs a concentration that is higher than 1%. During the second step the distribution and relationship between the elements that are present in the preliminary groups are characterized. As for glass, it does not seem useful to study the major elements into detail, because Roman (vessel) glass is known to have a very uniform main composition (Degryse ed. 2014, 24; Freestone 2005, 3). Trace elements, on the other hand, can be used to indicate small differences between glass types and are potential tracers for the raw materials in glass and their primary provenance (Degryse ed. 2014, 24). Therefore, the focus during the chemical analysis is on trace elements. Since glass contains many trace elements, the presence/absence classification used for metal has been replaced by an observation about the concentration of trace elements and the relations between the different concentrations. Naturally, the observed elements differ from those analysed for metal, considering that glass is a different material. The second step is performed in a similar manner than with metal, determining the similarities and differences between the (trace) elements and what this means into detail. This information has mainly been used to specify the primary origin of the glass and to look at recycling.

After the chemical interpretation, lead isotopic data was studied. This has been carried out as similar as possible for both materials. In this research, samples with lead isotope data are classified in time period, colour, provenance and recycling. Known chemical lead values are also taken into account. To back up and clarify the information, tables and plots have been made. The plots are made in the manner that is described in Pollard and Bray (2015), as sets of three diagrams. While making the plots, chemical and isotopic data are combined by plotting the chemical lead content against each lead isotope ratio. This has not only yielded information about the different classification groups, but also led to a potential determination of the lead sources from which the lead in the glass samples might originate. Finally, the interpretations of both the chemical and lead isotope analysis are combined with the idea to create a completer overview of the data. Only results of the other, previously made, analyses have been used to make this combined analysis.

When looking back at the plan of approach of the research proposal, it is clear that this research has not been performed or the deadlines met according to the initial work plan that was set up. This plan proofed to be too optimistic, due to several difficult analyses that took more time than anticipated. The researcher did not always had in-depth knowledge of all the specific subjects that are discussed in this research. Therefore, an addition to this knowledges through literature research was sometimes first necessary to be able to make the required data analyses.

2.2 Sampling

A total of 243 samples, from which chemical data is known, has been selected for analysis in this research. From 28 samples the lead isotope ratios are also known. All the samples were gathered during excavations in Sagalassos and because of export regulations only fragments of window and vessel glass were allowed to be collected as samples. Some samples have been measured multiple times, the information from these measurements is combined under one sample number. The samples are a collection of data from several researches that were previously carried out, they represent all the known samples from Sagalassos in a specific time frame, made from natron glass and with a known context. They concern pieces of vessel, window and chunk glass and show the common colours of glass finds from Sagalassos, both natural and artificial (e.g. green, blue, colourless, yellow-green and cobalt blue). The colours were distinguished macroscopically in earlier research. The chronology of the samples has been determined through stratigraphical association and all the samples are dated between 1 and 700 AD. In this research, four distinct time periods are indicated: period 1 (1-150 AD), period 2 (150-300 AD), period 3 (300-450 AD) and period 4 (450-700 AD). A fifth group, period X (unknown) makes the division complete.

2.3 Analytical procedure

Although no laboratory work has been performed especially for this research, the data that is used comes from previously done research in which laboratory work played an essential part. Most of the data, like chemical main and trace element contents or lead isotope values, could only be obtained through analyses in laboratories. The lab work was done by other researchers and is therefore not discussed into detail. Comprehensive accounts of these lab activities can be found in articles related to the lab work and the results (Degryse *et al.* 2005, 290, 291; Degryse *et al.* 2006, 496; van den Ostende 2015, 10-19). In short, for main and trace elemental analysis Atomic Emission Spectrometry (AES), Atomic Absorption Spectrometry (AAS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma Optical Mass Spectrometry (ICP-MS) were used. For only trace element analysis, Inductively Coupled Plasma Spectrometry (ICPS) and wavelength-dispersive X-ray fluorescence spectroscopy

(XRF) were also used. Besides that, Mass Spectrometry and Thermal Ionisation Mass Spectrometry (TIMS) were used for the Sr and Pb isotopic analysis. Lastly, thin-section petrography and X-ray Diffraction (XRD) were used to determine the mineralogical composition of glass samples.

3. Archaeological background

In this chapter an introduction about the site Sagalassos is given, both in general and focused on the glass (production) of the site. Furthermore, key concepts for this research are explained and discussed, like natron glass, recycling and the flow of glass.

3.1 The site Sagalassos

The city of Sagalassos is situated in south-west Turkey, in the ancient region Pisidia (fig. 3.1). Nowadays known as the Lake District in the provinces of Burdur, Isparta and Antalya (https://www.arts. kuleuven.be). It is located near the present-

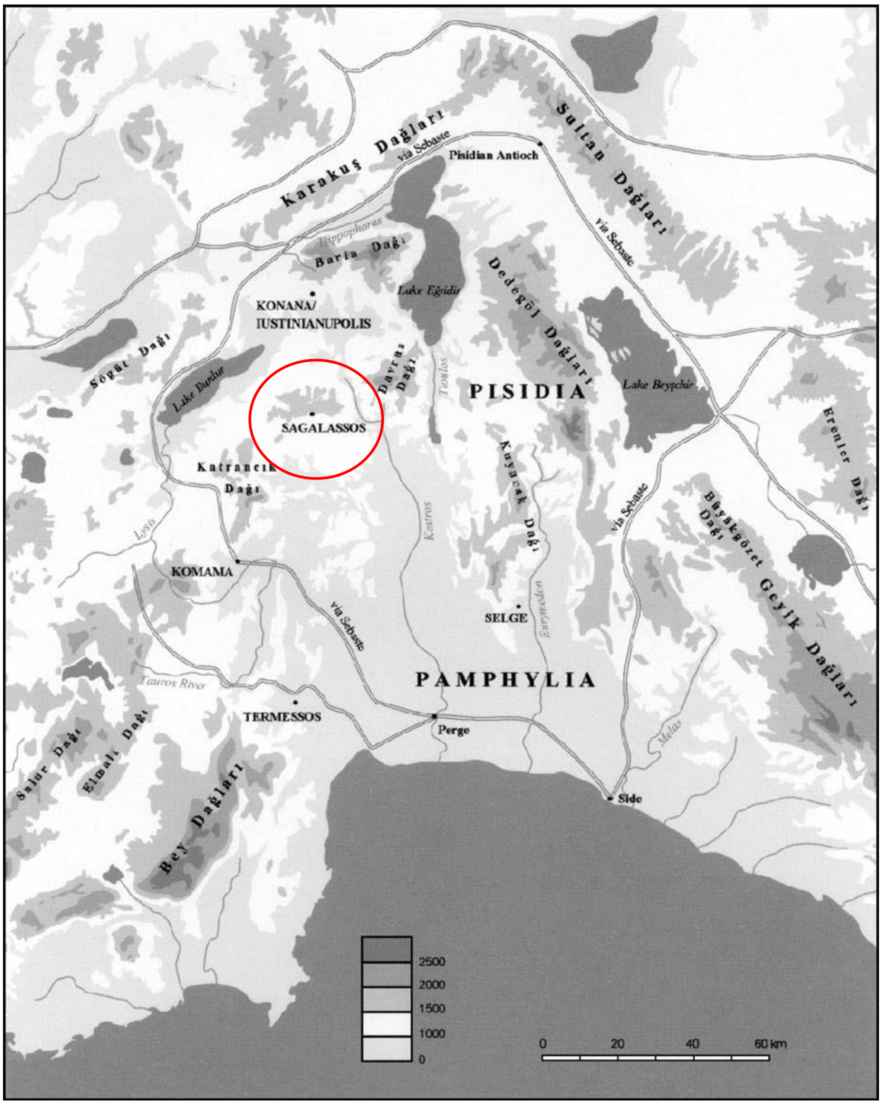


Figure 3.1: Map of the area of Sagalassos in south-west Turkey. The city lies in the red circle (Degryse et al. 2005, 288).

day town of Aglasun in the Taurus mountain chain and around 110 km north of the coastal city Antalya. At present, it is one of the best preserved known ancient cities in the Mediterranean and placed on the tentative list of UNESCO (https://whc.unesco.org).

The oldest traces of human activity in the area are dating around 10.000 BC in the Prehistory, long before the city Sagalassos was even built. From 6500 BC onwards permanent settlements were built in the region (Waelkens *et al.* 2011, 4). During and immediately after the Bronze Age the area came under the influence of different population groups, from which the Persians were the last. In 333 BC Alexander the Great conquered Sagalassos, starting the Hellenistic period. During the reign of several Hellenistic kings, Sagalassos started to expand from village to city (https://www.arts.kuleuven.be; Waelkens 2002, 313-321).

In 25 BC the city became part of the Roman province of Galatia and came under Roman rule, by Emperor Augustus. This period is marked by peace, expansion, the construction of public buildings and a road to the Mediterrenean Sea, economic development, mass production of high quality pottery and population growth (fig. 3.2). The first century AD can be seen as the golden age for Sagalassos (Waelkens 2002, 321-340; Waelkens *et al.* 2011, 5, 49). The city prospered under Roman rule and Sagalassos was the leading city in the region Pisidia until the late 3rd century AD (Waelkens 2002, 340-361; Waelkens *et al.* 2011, 5).

In the 4th century AD the Christian religion took hold of Sagalassos and caused a change in the appearance of the city. Such as the building of eight churches in the period of the 5th and 6th century AD (https://www.arts.kuleuven.be). The decline of the city started with an earthquake in the 6th century AD, followed by a plague epidemic and another earthquake in the beginning of the 7th century AD. On top of that, Arabs raided the city and region several times. It was thinly populated until the 13th century AD, in which all habitation ended (Degryse *et al.* 2006, 495; Waelkens *et al.* 2011, 6). Sagalassos was rediscovered by Paul Lucas in 1706, forgotten again at the end of the 19th century and came back into view in the 20th century through archaeological research by professor M. Waelkens. Excavations started in 1990 and the ancient city became the heart of an interdisciplinary research project co-performed by the University of Leuven (Degryse *et al.* 2006, 495; Waelkens *et al.* 2011, 7).

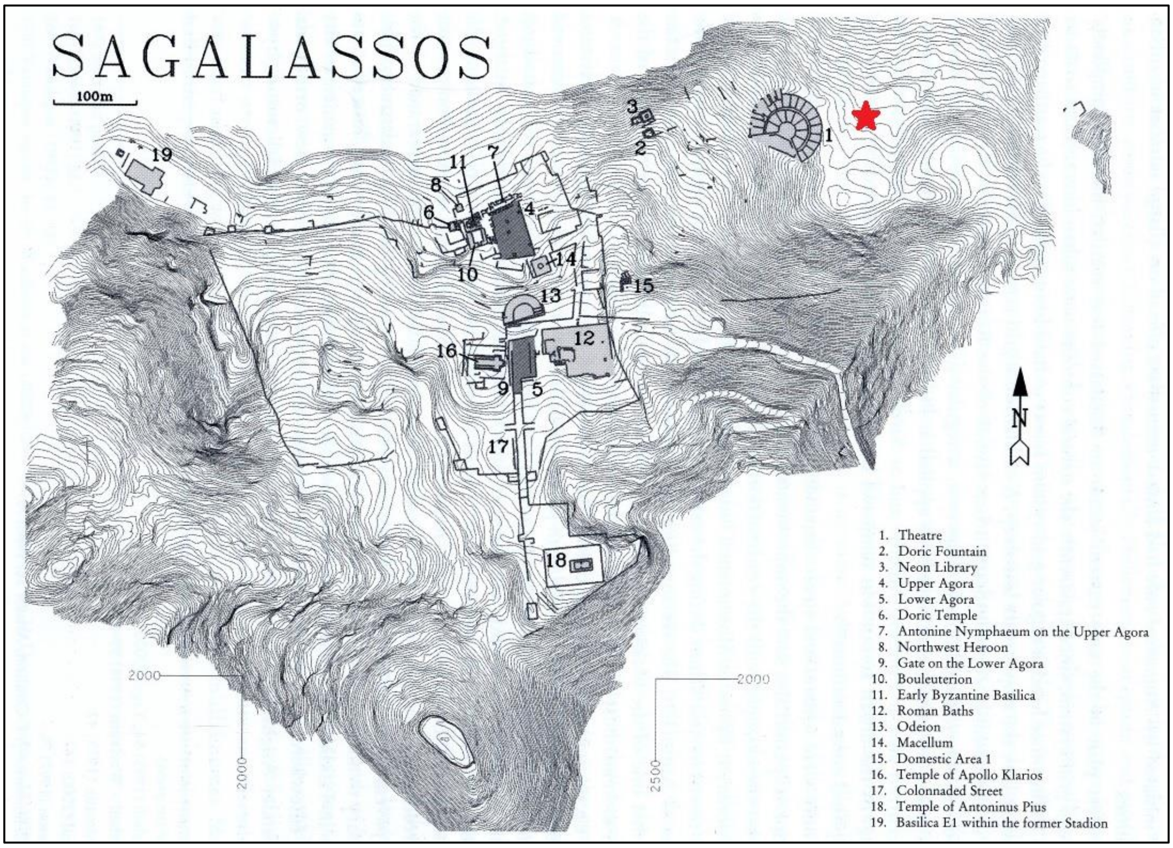


Figure 3.2: City map of Sagalassos, with the expansion of the occupied areas in early Imperial times to the east and to the south-west of the late Roman city walls. The red star shows the Potters Quarter/Eastern Suburbium (Waelkens 2002, 331 after F. Martens).

3.2 Natron glass and its production

Glass is made from a combination of three main raw materials; network formers, modifiers and stabilizers (Degryse ed. 2014, 20). Silica (SiO_2) is generally used as the network former in the form of sand or pure quartz. Since making pure silica glass requires a very high melting temperature, one that could not yet be achieved in ancient times, a modifier or fluxing agent was needed to lower the melting temperature. In ancient glass making, either soda (Na_2O) or potash (K_2O) was used for this. Lastly, lime (CaO) was often used as the stabilizer that was needed in order to secure the stability of the glass and its vulnerability to water. Sometimes silica sources that also contained lime were used for this, otherwise it was added in the form of limestone or shell (Degryse ed. 2014, 20; Degryse *et al.* 2014, 35; Ganio *et al.* 2012, 743).

The typical, high quality Roman soda-lime-silica glass that was made from the 5th century BC to the 9th century AD was made with the modifier soda, more precise a mineral form named natron. It was the most dominant glass type in the Mediterranean and surrounding areas in that time and owes its name, ‘natron glass’, to the addition of the similar named mineral (Degryse ed. 2014, 21, Freestone 2005, 3). The source for natron probably were evaporated soda-rich lake deposits in Egypt (Degryse and Braekmans 2014; Shortland *et al.* 2006). Characteristic for natron glass are its low magnesium and potassium concentrations, both beneath the 1.5%.

Typical for Roman glass in general is the relatively homogeneous major element composition (Degryse ed. 2014, 23). In order to produce the high quality glass, suitable sands, high in silica and free from or low in impurities, were needed. Preferably the natural concentration of lime in the sand was also high. This sand was not always easy to find and although suitable sources from the west Mediterranean are known, sand sources from the eastern Mediterranean were probably more numerous and more often used for glass production (Degryse ed. 2014). Besides the basic materials to make glass, other ingredients could be added intentionally, for example for colouring or decolouring glass. Like antimony or manganese for decolouring, cobalt for an intense blue colour or tin for an opaque white colour (Degryse and Braekmans 2014, 200; Ganio *et al.* 2012, 743; Henderson 1985).

Natron glass was manufactured on large scale, making glass objects common products in Roman time. There has been discussion about how this production took place, locally or centralised (Degryse 2016; Degryse *et al.* 2014). Research and archaeological evidence seem to increasingly back up the centralised approach, whereby glass was manufactured from raw materials in large primary production centres. In these centres no objects, but large glass slabs of several meters in length and tons in weight, were made. These were subsequently broken into pieces and traded through the whole Roman Empire. In Israel and Egypt archaeological remains of this kind of production have been found (Degryse ed. 2014; Degryse *et al.* 2014; Freestone 2005; Freestone *et al.* 2000; Nenna *et al.* 2000). This manner of glass manufacture is called primary glass production. The primary production was followed by secondary glass production, during which chunks of raw primary glass were worked and formed into vessels in workshops all over the Mediterrenean and Europe (Degryse ed. 2014; Freestone 2005). The glass was heated without melting it entirely, making it easier to (re)shape and finish the hot glass into objects (Degryse *et al.* 2005, 289).

3.3 Glass and its production at Sagalassos

Glass fragments of vessels and window panes are a group of finds that are practically always encountered during excavations in Sagalassos. Most of the glass finds were probably imported into the city, since no evidence for primary glass production has been found during excavations. However, secondary production, the working of glass, did occur at Sagalassos, as there are several indications to proof local manufacture (Degryse *et al.* 2005; 2006; Lauwers *et al.* 2007a, 6-8; 2007b). Workplaces for this were presumably situated in the eastern part of the town in an area of six hectares, east of the Theatre. Extensive pottery production took place in this part for six centuries long, giving it the name Potters Quarter. After the discovery that this area was also used for many other crafts, the name was changed into ‘Eastern Suburbium’ (red star in fig 3.2). For example, metal working and bone working took place there and it was used for waste disposal (Waelkens *et al.* 2011, 49). The area was used for crafts that were related to furnace activities, which is proven by the excavation of at least 15 kilns and 70 kiln-like structures (Lauwers *et al.* 2007a, 6).

Besides many small fragments, there are also parts of glass finds with a recognizable typology found in the city, like wine glasses, goblets or bottles (Lauwers *et al.* 2009, 8). The majority of the finds are free blown and were objects for daily use. However, there is also a small amount of glass finds that is identified as imported, fashionable and high quality glass (Degryse *et al.* 2005, 289). Amongst the glass found in the city, three main colour variations can be defined from the start of the imperial time, pale blue, pale green and colourless. Therefore, these colours are expected to be the ones mainly represented in the glass samples from this research. Pale blue glass was popular until around the second half of the 1st century. After that, the interest in blue glass decreased and the importance of pale green and colourless glass increased. Colourless glass became the most popular until the end of the 5th century AD. In the 4th century AD the interest in blue and green glass also experienced a revival. Furthermore, a fourth glass colour, yellow-green, was introduced. Around the time of the second earthquake the main colour was blue and the import of glass was considerably lower than before (Degryse *et al.* 2005, 289). Therefore, it is not surprising that the abandonment of the city can also been seen in glass finds (Lauwers *et al.* 2009). It will be interesting to see if these changes in colour and import through time can also be observed for the samples from this research.

3.4 Recycling

One of the key concepts of this research is recycling, reusing (old) materials to make something new. An extensive definition of the concept is: "*Recycling is an activity whereby a secondary material is introduced as a raw material into an industrial process in which it is transformed into a new product in such a manner that its original identity is lost. Secondary materials are those that (1) have fulfilled their useful function and cannot be used further in their present form or composition and (2) materials that occur as waste from the manufacturing or conversion of products*" (Darnay and Franklin 1972, 2, 3). Recycling in glass production is often related to the introduction of glass fragments or cullet into a glass batch (Degryse *et al.* 2006, 494). Cullet consist of broken and scrap glass that was collected and frequently used to melt down again in combination with new (primary) glass. Melting down a mixture of only scrap and waste glass could also be a possibility. In this way, broken, useless material became part of something new and could be used again. However, by combining various glass types, the composition and abilities of this newly created glass could differ significantly from the original glass types. Large quantities of cullet and broken glass are archaeologically known and were stored and traded throughout the Mediterrenean area in Roman time (Degryse *et al.* 2006, 495). This makes it more likely that they were indeed used for recycling. There are several indicators to recognize recycled glass based on its chemical composition, which are discussed in section 5.2.1.

There is a thin line between secondary glass production and recycling. When only raw glass from one primary production centre is used during secondary production, there is no change in the composition of the glass and there is no recycling involved. However, there is from the moment that several types of (primary) glass, glass cullet or fragments are combined and used to make new objects. It therefore seems that most of the times secondary production also involved some degree of recycling. There is chemical and isotopic proof for secondary glass production in Sagalassos (Degryse *et al.* 2006). Additionally, there are several other signs that point to local secondary production and recycling in Sagalassos. As a start, numerous pieces of broken glass, fuel ash slag, glass chunks and kiln fragments have been found (Degryse *et al.* 2006, 496). Also, the colour variety and technology of most glass assemblages is very similar. This implies a homogeneous composition of glass throughout the site, which can possibly be due to recycling. Moreover, many of the recovered objects had a modest functionality and only a low amount of special import items have been found. Besides that, there were available workplaces, kilns and quartz pebbles found in the Potters quarter and ancient riverbeds near Sagalassos that could have been used for glass production (Degryse *et al.* 2005, 289, 294). Lastly, a ceramic tool with an attached chunk of green glass has been found. It is believed that this tool represents a pontil rod or more precise a mandril, which was a tool used for glass working (Lauwers *et al.* 2007b).

3.5 Determining provenance

Provenance determination is another important element in this research. Concerning glass, provenancing is a way to determine the origin of the raw materials used in its production and/or the production location of the raw glass (Degryse ed. 2014, 22). The essence of provenance determination is the assumption that there is a measurable scientific property that can match an artefact with its (geological) source location. It is based on the idea that raw materials and the objects made from them have a similar signature or fingerprint than the geological source they originate from. Since glass loses many of its raw material characteristics during melting, the more stable and also characteristic chemical composition of glass is often seen as a chemical fingerprint and frequently used for assigning provenance (Degryse ed. 2014, 22, 23; Wilson and Pollard 2001, 507, 508). Provenance determination is based on several assumptions, which are discussed into detail in the article of Wilson and Pollard (2001, 507, 508). An important one is that geological sources or production centres have different chemical signatures and can therefore be used to originate raw materials. Overall, it is assumed that all the changes made in an object, from raw material to excavation, can be accounted for and that this object still contains (part of) the fingerprint of the raw material source.

Comparing chemical signatures from objects and geological sources can only confirm from which location an object did not originate (Degryse ed. 2014, 23). By ruling out all these locations, a possible provenance determination can be made. However, this will be more difficult if sources have similar signatures or if an objects has lost its original signature, for example through recycling. As said before, the chemical main composition of most Roman glass is very homogeneous. This means that the signatures of trace elements are necessary to originate the glass. Besides that, isotopic signatures or a combination of the two also have proofed to be very promising in determining provenance (Degryse and Braekmans 2014; Degryse and Schneider 2008; Degryse and Shortland 2009; Degryse *et al.* 2009).

These techniques make it possible to compare very small variations in signatures of geological sources around the Mediterrenean Sea (Degryse ed. 2014, 24). A combination of trace element and isotopic signatures is also used in this research to determine the provenance of the glass samples.

Pollard *et al.* (2014, 625) refer to the above explained provenance determination as 'Traditional Provenance'. They argue that the Traditional Provenance model is flawed, especially when looking at copper alloys (Bray *et al.* 2015). Although they admit the key aspects of Traditional Provenance are useful for linking the 'initial source' with the 'final artefact', they disagree with the simple linear models that are often used for this (Bray *et al.* 2015; Pollard *et al.* 2014). They argue that steps are missing in these models, in specific about social and technological change, and it is therefore not possible to create a complete overview of provenance. The Traditional Provenance almost never takes the time that is needed for an object to move from primary extraction of raw materials to archaeological deposition into account (Bray *et al.* 2015, 205). Most provenance studies assume that movement between source and deposition is instantaneous, using a social and economic model similar to modern trade (Pollard *et al.* 2014, 626). However, an object can also end up in a deposition through indirect trade or after hundreds of years of (re)use. It is therefore important to consider questions about time and change when determining provenance. Pollard *et al.* (2014, 630) suggest two ways to include time in the analysis. 1. Dating the start and end point of the trail. 2. Finding some form of a relative internal clock which represents distance and time. They propose the following replacement of the 6th assumption listed by Wilson and Pollard (2001) in order to complement the current concept of Traditional Provenance: "*We must evaluate the chronological dimension of the proposed movement of material, which can then be used to suggest the social, geographical and temporal characteristics of the movement"* (Pollard *et al.* 2014, 631). In this research the 6th assumption is taken into account and together with the concept of flow is used to create a complete provenance determination.

3.6 Concept of flow

The concept of flow is understood as an overview or characterization of the dynamic life history of objects, which include many compositional (elemental and isotopic), social and context transformations. It can be seen as a dynamic system, full of change and the consequences these changes bring about (Bray *et al.* 2015; Pollard and Bray 2015). The meaning of using the concept flow is to characterise the changing nature of materials in circulation. Next, these observations can be used to create a complete life history of objects/materials. In order to define the changes in materials a data-led approach is necessary. Several snapshots of flow, like specific moment in time, can be observed and compared with each other. A complete overview of the flow of specific materials or objects through time can be made by determining the known snapshots, what consequence they had, how was reacted on these consequences, did this led to change in composition/social meaning/context of the material, etc. By looking at all these aspects and placing them into context, flow can be mapped step by step (Bray *et al.* 2015; Pollard and Bray 2015).

4. Research results

In this chapter an overview of the results is presented. The most important results are the two databases made in Excel that contain most of the data used in this research (appendix 3). Since this are separate documents, it is difficult to write down all the data from them in this chapter. Therefore, the databases are referred to for the most complete overview of the results. Moreover, some results are integrated in the analysis and are both presented and discussed in chapter 5.

4.1 Data for provenance and recycling analysis

A total of 268 measurements is documented in the database related to provenance and recycling analysis. There are 25 double measurements of which data is combined under one sample number, making the total amount of different samples 243. There are 33 samples that date in P1, 20 in P2, 43 in P3, 130 in P4 and 17 in Px (table 4.1). Colourless glass is the most abundant, with 101 samples. 62 samples are green coloured, 39 are blue and 16 samples have other colours. 9 cobalt blue samples, 13 yellow-green (himt) and 3 purple samples are colours that only occur in P4 (table 4.1). The glass samples are mostly fragments of vessels, but also fragments of windows and glass chunks are used (table 4.2).

Table 4.1: Overview of the amount of samples in each time period for the different glass colours.

Period	Colourless	Green	Aqua/blue	Cob. Blue	Yellow-green (himt)	Purple	Other	**Total**
P1	12	8	11	0	0	0	2	**33**
P2	10	2	4	0	0	0	4	**20**
P3	31	8	1	0	0	0	3	**43**
P4	41	37	20	9	13	3	7	**130**
Px	7	7	3	0	0	0	0	**17**
Total	**101**	**62**	**39**	**9**	**13**	**3**	**16**	**243**

There are 82 samples with the provenance Egypt Alexandria, 79 are from Syro-Palestine, 45 originate in Egypt HIMT, 7 have a west Mediterranean provenance and for 30 samples the provenance is unknown (table 4.3). The data about recycling is presented in many small, detailed tables in appendix 1. These were used to make the tables with overviews of the recycling data in chapter 5.

Table 4.2: Overview of the type of glass for each time period, in amount of samples.

Period	Vessel	Window	Chunk	Jewellery	Deformed piece	?	**Total**
P1	31	0	1	0	1	0	**33**
P2	18	1	1	0	0	0	**20**
P3	39	1	2	1	0	0	**43**
P4	97	15	10	1	0	7	**130**
Px	13	2	2	0	0	0	**17**
Total	**198**	**19**	**16**	**2**	**1**	**7**	**243**

Table 4.3: Overview provenance groups for each time period, in amount of samples.

Period	Syro-Palestine	Egypt HIMT	Egypt Alexandria	West Mediterranean	Unknown	**Total**
P1	9	2	13	5	4	**33**
P2	9	1	7	2	1	**20**
P3	14	3	16	0	10	**43**
P4	40	35	43	0	12	**130**
Px	7	4	3	0	3	**17**
Total	**79**	**45**	**82**	**7**	**30**	**243**

4.2 Data for lead isotope analysis

In total there are 40 measurements for which the lead isotope ratios are calculated. Because there are 12 double measurements, the amount of different sample numbers is 28. For 16 of these 28 samples both the lead isotope ratios and the chemical lead content are known.

Table 4.4: Samples with lead isotope data classified in the different glass colours.

Period	Colourless	Green	Aqua/blue	Cob. blue	Yellow-green (himt)	**Total**
P1	1	2	4	0	0	**7**
P3	2	0	0	0	0	**2**
P4	3	4	6	1	5	**19**
Total	**6**	**6**	**10**	**1**	**5**	**28**

Table 4.5: Samples with lead isotope data classified in the different provenance groups.

Period	Syro-Palestine	Egypt HIMT	Egypt Alexandria	West Mediterranean	Unknown	**Total**
P1	3	0	4	0	0	**7**
P3	0	0	2	0	0	**2**
P4	5	9	4	0	1	**19**
Total	**8**	**9**	**10**	**0**	**1**	**28**

Table 4.6: Recycling for samples with lead isotope data.

Period	No	Yes	Unclear	**Total**
P1	2	3	2	**7**
P3	1	0	1	**2**
P4	4	3	12	**19**
Total	**7**	**6**	**15**	**28**

The 28 samples have been classified in time period, glass colour, provenance and recycling (table 4.4 – 4.6). P1 contains 7 samples, P3 2 and P4 19. There are no samples with lead isotope data available for the other time periods. Of the 28 samples, 6 are colourless, 6 green, 10 aqua/blue, 1 cobalt blue and 5 have a yellow-green colour (typical for HIMT glass) (table 4.4). 8 of the samples originate from Syro-Palestine, 9 have the provenance Egypt HIMT, 10 are from Egypt Alexandria and for 1 sample the provenance is unknown (table 4.5). Finally, 7 samples are not recycled, 6 are recycled, while for 15 samples this is unclear (table 4.6).

Table 4.7: Overview of all the lowest and highest ratios of the lead isotope ratios and the chemical lead content, for 28 glass samples.

	Lowest ratio/value	**Highest ratio/value**
^{206}Pb/^{204}Pb	18,167	18,859
^{207}Pb/^{204}Pb	15,632	15,728
^{208}Pb/^{204}Pb	38,407	38,881
^{207}Pb/^{206}Pb	0,831	0,865
^{208}Pb/^{206}Pb	2,054	2,125
Chemical lead content (in ppm)	5 ppm	214 ppm

The total ranges of the lead isotope ratios can be found in table 4.7, in which the lowest and highest ratios are presented. The chemical lead content ranges from 5 to 214 ppm. 11 samples have a low to medium lead content (5-100 ppm) and 5 samples a high lead content (100-214 ppm).

Table 4.8: Overview of the 16 samples from which both the lead isotope ratios and the chemical lead content are known (EA=Egypt Alexandria, SP= Syro-Palestine, HIMT= Egypt HIMT).

Sample	**Period**	**Colour**	**Provenance**	**Recycled**	**Pb (in ppm)**
574	1	Colourless	EA	No	10
721	1	Pale green	SP	No	7
723	1	Pale green	EA	Yes	130
572	1	Aqua	EA	Yes	44
577	1	Aqua	EA	Yes	143
579	3	Colourless	EA	No	61
588	4	Colourless	SP	Unclear	40
593	4	Colourless	SP	Unclear	5
594	4	Colourless	SP	Yes	214
727	4	Pale green	HIMT	No	48
729	4	Pale green	HIMT	No	66
582	4	Aqua	SP	No	80
583	4	Aqua	SP	Yes	123
590	4	Aqua	EA	Yes	160
720	4	Yellow-green (himt)	HIMT	No	9
Giessen	4	Yellow-green (himt)	HIMT	Unclear	24

Looking at the 16 samples, 5 are dated in P1, 1 in P3 and 10 in P4 (table 4.8). 5 samples are colourless, 4 green, 5 aqua and 2 yellow-green coloured. 6 samples have the provenance Egypt Alexandria, 6 are from Syro-Palestine and 4 from Egypt HIMT. For 3 samples recycling is unclear, 7 samples are unrecycled and 6 are recycled.

5. Data analysis and discussion

In this chapter the collected data about 243 glass samples from Sagalassos is analysed and discussed in order to determine possible provenance areas, the amount of recycling and the influence of lead isotope ratios. From some sample numbers multiple measurements are available. The information from these measurements is combined and taken into account as one sample in the analysis and data overviews. The glass samples are divided in five time periods: P1 (1-150 AD), P2 (150-300 AD), P3 (300-450 AD), P4 (450-700 AD) and Px (unknown). First a separate provenance (section 5.1), recycling (section 5.2) and lead isotope analysis (section 5.3) are presented. These are all combined in section 5.4, in which an overview of the life history of the Sagalassos glass flow is discussed.

5.1 Provenance

Based on literature research, five likely provenance groups have been characterized in which the 243 glass samples from Sagalassos are classified. These groups are: 1. Syro-Palestine 2. Egypt HIMT 3. Egypt Alexandria (/south Italy) 4. West Mediterranean 5. Unknown. The recycling of glass is also indicated, but recycled glass is not considered as a separate provenance group. In section 5.1.1 the provenance groups are introduced and the criteria and chemical threshold values for the groups are discussed. An overview of the thresholds for all the provenance groups is presented in table 5.2. A critical note that should be taken into account is that most of these criteria are not insensitive to glass recycling or mixing. Therefore, sample values can vary from the average provenance criteria. Although a provenance can often still be determined, it is sometimes less clear. After the introduction, the primary origin of the glass from Sagalassos and what this means is discussed in section 5.1.2.

5.1.1 Introduction of the provenance groups

Syro-Palestine

Syro-Palestine is also known as the Levant I (e.g. glass from Dor, Apollonia and Jalame) and the Levant II (e.g. glass from Bet Eli’ezer) provenance groups. To determine the criteria and threshold values for the provenance group Syro-Palestine, the chemical values of primary glass finds and information from other literature were taken into account. Multiple primary glass finds with this provenance made it possible to determine the mean chemical values of the glass (table 5.1)

(Freestone and Gorin-Rosen 1999; Freestone *et al.* 2000; Freestone *et al.* 2003; Freestone 2005; Freestone 2006; Freestone *et al.* 2008; Henderson 2002). Based on this mean chemical values and information from additional literature (Degryse 2016, 4; Degryse ed. 2014, 104; Degryse, Scott and Brems 2014, 39; Freestone *et al.* 2009, 33) the threshold values for the Syro-Palestine provenance group have been determined and are noted down in table 5.2.

Glass from Syro-Palestine is produced from the middle of the 1st millennium BC until the 9th century AD in the eastern Mediterranean area. It is the most commonly found glass type in the Mediterranean and occurs in various colours, such as naturally coloured (e.g. pale green and blue), strongly coloured (e.g. cobalt blue and opaque) and colourless glass (Degryse, Scott and Brems 2014, 40; Freestone 2006, 2). It often makes up a considerable part of glass assemblages (Degryse ed. 2014, 106). Because of this, the largest part of the glass from this research is expected to have a Syro-Palestine provenance. Archaeological evidence for both primary and secondary production of this glass have been found, in the form of raw chunk glass, tank furnaces, (recycled) vessels and (recycled) scrap glass (Freestone 2003; Freestone *et al.* 2000). Sand from the Levantine coast is a key ingredient and accounts for most of the material composition of the glass (around 70%).

Table 5.1: Mean chemical values of primary glass finds in Syro-Palestine.

Criteria/threshold values	**Syro-Palestine**
SiO_2	Around 70% Min: 64% Max: 77%
Al_2O_3	Around 3% Min: 2.4% Max: 4.22%
FeO	Around: 0.35-0.50% Min: 0.24% Max: 1.35%
MnO	<0.10%
MgO	Around: 0.60% Min: 0.50% Max: 0.92%

CaO	Around: 7-9% Min: 5.45% Max: 11.47%
Na_2O	Around: 12-17% Min: 10.28% Max: 18.87%
K_2O	Around: 0.50 – 1% Min: 0.35% Max: 1.42%
TiO_2	Around or < 0.10% Min: < 0.10% Max: 0.19%
P_2O_5	Around: 0.10% Min: < 0.10% Max: 0.18%
Zr	Around: 50–70 ppm Min: 45 ppm Max: 90 ppm
Sr	Around: 350–500 ppm Min: 230 ppm Max: 498 ppm
Cl	Around: 0.80% Min: 0.36% Max: 1.04%

Egypt HIMT

HIMT glass is glass with a high iron, magnesium, manganese and titanium content. All these chemical elements are correlated with each other and with the aluminium content (Freestone *et al.* 2003, 154). There is no archaeological evidence for primary glass furnaces that produced HIMT glass (Freestone 2005, 11), therefore there are no chemical values of primary glass that can be used to determine the thresholds of the provenance group. However, (raw) chunk HIMT glass has been found in multiple places spread across the Mediterranean and Europe (e.g. Cartage, North Sinai, London and Cyprus) and the chemical composition of this glass can be used to determine thresholds (Freestone 2003, 112; Freestone 2005; Freestone 2006; Freestone *et al.* 2003). Additional information about the threshold values and the Nd isotopic signature of HIMT glass can be found in Degryse ed. (2014, 104) and Degryse, Scott and Brems (2014, 39). This combined information led to the threshold values for the provenance group of HIMT that are noted down in table 5.2.

HIMT glass probably was the most abundant glass type used in Europe and the Mediterranean in the 4th to 5th century AD. It was a new type of glass that quickly became widespread. Although no primary production centres have been found, raw chuck glass from shipwrecks is known (Freestone 2003, 112). The primary origin of the glass is expected to be somewhere in Egypt (Degryse et al 2008, 54; Freestone *et al.* 2003, 155). The glass has a typical yellow-green to olive-green colour and is transparent. The complex chemical composition of HIMT glass is caused by the mixing of two different sands. These probably were a beach or marine sand and a sand that was enriched with non-marine material (rich in iron, magnesium, titanium and aluminium). The raw glass does not seem to be made through recycling, but from a mix of two different types of primary glass (Freestone *et al.* 2003, 154, 155).

Egypt Alexandria (/south Italy)

This provenance group is not determined in the work of Freestone and co-workers. The first indications for glass production near Alexandria, besides Lake Maryut, are excavated glass furnaces (Nenna *et al.* 2000). Subsequently, based on the suitability of available sand sources in this area and similar sources in the south of Italy, this new primary provenance group was introduced (Degryse 2016; Degryse ed. 2014; Degryse, Scott and Brems 2014). The information from literature together with chemical values of (primary) glass samples (Degryse 2016; Ganio *et al.* 2012) determine the threshold values and the Nd isotopic signature that are noted down in table 5.2. Since all the known primary glass production centres are situated in the eastern Mediterranean, it is more likely that the provenance of this primary glass is Egypt, near Alexandria, than the south of Italy. Therefore, in this research, the provenance group will mainly be referred to as 'Egypt Alexandria'.

Glass with the provenance Egypt Alexandria is mostly dated between the 1st and 4th century AD (Degryse 2016, 4). Apart from the alumina content, which is much lower, it is quite comparable to Syro-Palestine glass. The excavated glass furnaces near Alexandria, at Lake Maryut, date until the 8th century AD. The glass is often colourless through decolouration by antimony (Sb) and the glass found at Lake

Maryut generally has a low lead content, showing few signs of recycling (Degryse 2016, 4). However, there is no evidence that recycling did not occur at all or that other colours were not produced.

West Mediterranean

There are no primary glass production centres from archaeological excavations known outside the eastern Mediterranean (Degryse ed. 2014, 104; Freestone 2006, 10). Therefore, no chemical values of primary glass are available to use as comparable source material to determine the threshold values of the west Mediterranean provenance group. The introduction of this provenance group is based on available sand sources along the west Mediterranean coast that were suitable to make Roman natron glass (Brems *et al.* 2012a; Brems *et al.* 2012b; Degryse ed. 2014). Furthermore, work of the ancient author Pliny also proposed that raw materials from the west Mediterranean were used in the production of glass (Degryse and Schneider 2008). Some chemical data, threshold values and the Nd isotopic signature of western Mediterranean glass are discussed in Degryse ed. (2014) and Degryse (2016). This information has been used to determine the threshold values in table 5.2. Since only a few threshold values could be defined, this provenance group will be the hardest to determine. At the moment, εNd values are the only data that can be used to associate glass samples with a west Mediterranean provenance with a high degree of certainty (Degryse 2016, 4; Degryse and Schneider 2008). Although the occurrence of primary glass production in the western Mediterranean is not yet fully proved, it is most probable (Degryse ed. 2014). Therefore, the provenance group is included in this research.

Glass with a west Mediterranean provenance appears in the 4th century BC, but mostly from the 1st to the first half of 5th century AD (Degryse ed. 2014, 106, 107). Along the west Mediterranean coast, six areas can be found with suitable sand for making Roman natron glass. These areas are situated in Spain, France and Italy (Degryse ed. 2014, 48, 49). Although these areas contain suitable raw materials to produce glass, few glass samples with a west Mediterranean provenance are actually known. This makes it hard to determine the exact thresholds of the provenance group. In the glass analyses of Degryse ed. (2014) and Degryse (2016) 5% (16 samples) of all the samples have a western Mediterranean provenance. These glass samples come from 11 different sites and are naturally coloured or colourless (Degryse ed. 2014, 106). Since only a few samples with this origin are known, it is suspected that the glass was frequently recycled in later times. However, only a quarter of the glass samples presented in Degryse (2016, 5) have such a high lead content that it indicates recycling, which is less than expected.

Unknown

The group unknown is a mix of different samples and has no threshold values. It contains samples from which no reliable provenance can be defined and all the samples that do not fit in the other provenance groups. A provenance determination is less reliable if it is based on only a few chemical values.

Table 5.2: Overview of criteria and threshold values for the provenance groups.

Criteria/ threshold values	**Syro-Palestine**	**Egypt HIMT**	**Egypt Alexandria (/south Italy)**	**West Mediterranean**
SiO_2	Around 70% Between 64-77%	Around 65% Between 60-67%	Around 70% Between 60-73%	Not known
$Al2O_3$	Around 3% Between 2-4.2%	Around 2.5-3% Between 2-3.5%	Around <2% Max. 2.5%	Between 0.9-3.8%
FeO/ Fe_2O_3	Around 0.35-0.5% Between 0.2 – 1.35%	Around 1-2% Between 0.7-5%	Around 0.3% Between 0.1-0.5%	Not known
MnO	<0.1%	Around 1.5-2% Between 1-5%	Around 0.3-0.4% Between 0.01-1.5%	Not known
MgO	Around: 0.6% Between 0.5-0.9%	Around 1% Between 0.9-1.4%	Around 0.4% Between 0.2-0.6%	Between 0.3-1.12%
CaO	Around: 7-9% Between 5.5-11.5%	Around 6% Between 5-8%	Around 6% Between 4.5-9%	Between 5-10.2%
Na_2O	Around: 12-17% Between 10-19%	Around 18% Between 16-20%	Around 18% Between 14-20%	Not known
K_2O	Around: 0.5 – 1% Between 0.35-1.4%	Around 0.45% Between 0.3-0.8%	Around 0.4% Between 0.3-0.6	Between 0.24-1.18%
TiO_2	Around or < 0.1% Between 0-0.2%	Around 0.3-0.6% Between 0.1-1%	<0.1%	Between 0.06-0.26%
P_2O_5	Around: 0.1% Between 0-0.2%	Not known	Not known	Not known
Zr	Around: 50 – 70 ppm Between 0-90 ppm	Elevated (?)	< 80 ppm	Not known
Sr	Around: 350 – 500 ppm Between 200-550 ppm	Not known	Not known	Not known
Cl	Around: 0.8%	Not known	Not known	Not known

	Between 0.35-1.05%			
εNd	> -6.0	> -6.0 Between -4.0 and -6.0	> -6.0	Between -12.0 and -6.0/-7.0
$^{87}Sr/^{86}Sr$	Between 0.7088-0.7092	Between 0.7075-0.7090	Between 0.7087-0.7091	> 0.7092 (?)
Other		Ba elevated		

5.1.2 Provenance of the Sagalassos glass

When the provenance for the glass samples from Sagalassos was determined for the first time, the difference between groups was hard to make and the used criteria and threshold values proved to be insufficient. Over 70% of the samples was classified in the group Unknown. Since these results were far too general to be of use, more extensive literature research was carried out, to specify the criteria and thresholds of each provenance group. These criteria and threshold values were used to revise the first interpretations, which led to a reliable and precise provenance of the samples. Overall, the provenance of the 243 glass samples is, 33.7% Egypt Alexandria, 32.5% Syro-Palestine, 18.5% Egypt HIMT, 12.4% Unknown and 2.9% west Mediterranean (table 4.3 and 5.3).

The two largest provenance groups are Egypt Alexandria with 33.7% (82 samples) and Syro-Palestine with 32.5% (79 samples). According to literature, from which it is known that most of the primary glass production took place in the eastern Mediterranean, these two groups were expected to be the most substantial. However, it is striking that the largest part of the samples seems to originate in Egypt near Alexandria, because glass from Syro-Palestine is more common in other known glass studies (Degryse ed. 2014; Freestone 2003; Freestone 2005). Since glass with the Egypt Alexandria provenance is recognized for about 20 years, this provenance is not included in older researches. This might explain the better known and more often mentioned provenance of Syro-Palestine in literature. The most notable difference between the two provenance groups is the alumina content in the glass, which is low in glass from Egypt Alexandria. The total amount of glass from Egypt Alexandria seem to decrease slightly over time, from 39% in P1 to 33% in P4. The amount of Syro-Palestine glass is more constant through time, around 30% in P1, P3 and P4, with the exception of 45% in P2. The continuous presence of these two provenance groups, through all the time periods, corresponds with literature, in which it is stated that glass was produced in the eastern Mediterranean, mainly Syro-Palestine, from the middle of 1st millennium BC to 9th century AD (Degryse, Scott and Brems 2014, 40). It is noteworthy that in P3 and P4 also many samples from Egypt Alexandria are present. Although glass with this provenance was definitely produced until the 8th century AD, it mainly occurred from the 1st to 4th century AD.

The third largest group is Egypt HIMT with 18.5% (45 samples). Corresponding to literature, it was mainly produced and available from the 4th century onwards (P3 and P4) (Freestone *et al.* 2009, 40). Surprisingly, there are a few samples with this provenance that can be placed in P1 and P2. Even though this does not agree with the information from literature, it concerns only 3 samples, which are perhaps dated incorrectly. This glass group is most abundant in P4, around 27% of all the samples from P4 have this provenance.

Only 2.9% (7 samples) of all the glass samples has a west Mediterranean provenance. There are several reasons why this provenance is not that common. To begin with, glass with this provenance is not yet widely known and therefore hard to recognize and to determine. Based on literature, no more than around 5-10% of the samples was expected to originate from the west Mediterranean region (Degryse 2016, 5; Degryse ed. 2014, 106; Degryse, Scott and Brems 2014, 42). Knowing this, it is unlikely that a large part of the glass from Sagalassos originates from the west Mediterranean. Furthermore, the west Mediterranean production stops somewhere in the 4th century AD and the glass signature slowly dies out over time (Degryse ed. 2014, 112; Degryse, Scott and Brems 2014, 42). Accordingly, this perhaps explains why samples with this origin only occur in P1 and P2 and are not encountered in P3 and P4.

Around 12% (30 samples) of the samples is classified in the group ‘unknown’. This group contains a strange mix of samples that do not fit into the other provenance groups. 10 of the samples can possibly, with high uncertainty, be linked with one of the other known provenances and 20 cannot be related to any known provenance group at all. Since more than half of these 20 samples have indications for recycling, the signatures of these samples can perhaps be too mixed to determine a provenance. The samples that have no indications for recycling might originate from a yet unknown glass production site or new provenance area.

The glass samples also have been subdivided according to colour. However, the different colours of the glass do not clearly correspond with certain provenance groups. In every provenance group, samples from all main colours are present.

Table 5.3: Overview provenance groups for each time period, in percentages.

Period	Syro-Palestine	Egypt HIMT	Egypt Alexandria	West Mediterranean	Unknown	**Total**
P1	27,3	6,1	39,4	15,2	12,1	**100%**
P2	45	5	35	10	5	**100%**
P3	32,6	7	37,2	0	23,3	**100%**
P4	30,8	26,9	33,1	0	9,2	**100%**
Px	41,2	23,5	17,6	0	17,6	**100%**
Total	**32,5%**	**18,5%**	**33,7%**	**2,9%**	**12,4%**	**100%**

5.2 Recycling

Glass recycling has already been mentioned in the former section and is again linked with provenance in this section. Similar to provenance, criteria to determine recycling are based on literature research. The indications to recognize recycled glass are discussed in section 5.2.1. These criteria have been used to analyse the glass samples from Sagalassos and the result of this analysis is considered in section 5.2.2.

5.2.1 Indications for recycling

To indicate recycling, three groups are used: not recycled (No), recycled (Yes) and unclear (?). To determine recycling in ancient glass, three main criteria or indications are analysed. If one or more of these criteria agrees with the chemical composition of a glass sample, than this clearly indicates recycling (Degryse 2016; Degryse ed. 2014). These criteria are: 1. MnO > 0.1% and Sb > 30 ppm 2. Pb between 120 and 1500 ppm 3. Co, Ni, Cu and/or Zn between 100 and 1000 ppm.

The 1st criteria is based on the presence of manganese oxide (MnO) and antimony (Sb) in the samples, which are both used as decolourisers in glass. Since only one of these two is needed for decolouration, the presence of elevated levels of both elements points to deliberate addition or recycling (Degryse ed. 2014, 85). The 2nd criteria is related to lead (Pb) in glass and is considered a very reliable indicator for recycling. An amount of less than 100 ppm in glass is probably unintended and the result of pollution of the raw materials. In Roman glass, a lead content of more than 100 ppm represents either recycling or an addition for colouring the glass (Degryse 2016, 5; Degryse ed. 2014, 105). A presence of (several) thousands ppm implies intentional addition. The 3rd criteria concerns chemical elements that are generally associated with the (de)colouration of glass. An extensive group of elements can be considered: Mn, Co, Ni, Cu, Zn, As, Se, Ag, Cd, In, Sn, Sb, Au, Hg (Degryse ed. 2014, 72). However, of all these elements only Co, Ni, Cu and Zn values are known from the glass from Sagalassos. Therefore, only these four chemical elements are looked at. High concentrations of these elements, more than 1000 ppm, relate to deliberate addition for colouration. A presence between the 100 and 1000 ppm indicates recycling, because it is too low to deliberately influence the colour of glass and too high to explain as pollution in the raw materials (Degryse ed. 2014, 73; Silvestri *et al.* 2005, 811).

After the criteria are analysed, the recycling can further be specified. If none of the above standing criteria are met, the glass is either certainly unrecycled or it is not known if it is recycled or not. If enough chemical elements from a sample are analysed, criteria can be ruled out or predicted to never be possible. In this excluding way, recycling can be ruled out with a high amount of certainty. If not enough chemical elements of a sample are analysed, there is frequently not enough information available to determine or rule out recycling. Such a sample is placed in the group Unclear. This group contains all the samples from which it is not apparent if they were recycled or not.

5.2.2 Recycling of the Sagalassos glass

According to the current chemical data, 27.5% (67 samples) of the total of 243 samples is not recycled (No), 30.5% (74 samples) is recycled (Yes) and for 42% (102 samples) this is unclear (?) (table 5.4). Due to the limited chemical element analysis of samples that was available to indicate recycling, it was hard to determine recycling and thus the group unclear is the most substantial. Furthermore, some chemical values were noted down in different units and needed to be converted, which made these values sometimes difficult to use in data overviews. Although the unclear part is quite considerable, for more than half of the samples recycling or not is determined with certainty and these samples can be used for a reliable analysis. The amount of samples that is and is not recycled lies close, which makes it plausible that both recycled and unrecycled samples are present in the unclear group. However, it is difficult to presume the final ratios of the recycled and unrecycled glass. Since there are recycled samples through all time periods, it is also clear that glass recycling definitely was something that occurred from 1 to 700 AD.

Table 5.4: Overview of recycling in the whole dataset, in amount of samples and percentages.

	No	Yes	?	**Total**
Amount of samples	67	74	102	**243**
% of dataset	27,5%	30,5%	42%	**100%**

Recycling through time

The highest amount of recycled glass can be determined in P2 with 35%. However, with 27.3% recycling in P1, 30.2% in P3 and 29.2% in P4, the overall recycling through time is quite stable around 30% (table 5.5 and appendix 1). The differences between the time periods consist only of a few percent and are insignificant. Because some groups only contain a small amount of samples and are therefore unsuited to use for detailed statements. Even though P2 seems the period with the most recycling, it is only the period with the most certain recycling. For example, for 45% of the samples in P1 and P4 it could not be determined if the glass was recycled or not. It therefore needs to be taken into account that these periods can contain much more recycled samples than is known at the moment.

Around 25-27% of the glass from P1, P3 and P4 is not recycled for certain. With 45% unrecycled glass, P2 tops this by far. It is striking that P2 is the period with both the most recycling of all four periods and a larger part (45%) not recycled glass, than recycled glass (35%). An explanation for this is that recycling or not could be determined with certainty for a large share of the glass in P2 and in other periods it could not.

The recycling is unclear for around 45% of the glass from P1 and P4, 20% from P2 and 42% from P3. With 41.2%, the amount of glass that is recycled from Px is high. Further, 23.5% of the samples in Px is not recycled and for 35.3% this is not known. It is not really effective to compare Px with the other time periods, because the samples in this group should fit into the other groups somewhere and therefore a comparison can cause mixed signatures.

Besides in P2, the overall recycling through time is quite stable, with about 30% recycled glass, 26% unrecycled glass and for 43% recycling is unclear (table 5.5).

Table 5.5: Total amount of recycling for each time period, in percentages.

Period	**No**	**Yes**	**?**	**Total**	**More or less mixing**
P1	27,3	27,3	45,4	100%	
P2	45	35	20	100%	More than P1
P3	27,9	30,2	41,9	100%	Less than P2
P4	25,4	29,2	45,4	100%	Less/similar than P3
Px	23,5	41,2	35,3	100%	

Recycling and glass colours

The colourless glass samples form a group that is very useful for this analysis, because it contains the most samples (101) and has the highest amount of samples determined for recycling (table 5.6 and appendix 1). Overall, around 46% is not recycled, 24% is recycled and for 30% this is unclear. It can be concluded that colourless glass was mostly produced in primary production centres. This is especially clear in P1, P2 and P4. However, there are some recycled samples, which indicate that recycling also occurred with this type of glass. In P3 this mixing is clearer than in the other time periods. According to the chemical data, the amount of glass that is recycled increases from P1 to P3, followed by a decrease in P4.

Green glass is the second largest group (62 samples) and seems to have been produced in both primary centres and through recycling. Over time, the amount of recycled green glass from Sagalassos is always similar or higher than the amount of not recycled glass. Overall, 21% is not recycled, 37% is recycled and for 42% this is unclear. Except for P2, the amount of recycling does not seem to change significantly over time. It is highest in P2 (2 recycled samples) and P4 (14 recycled samples).

The group of aqua/blue glass (39 samples) is smaller than the green group and also seems to be made largely from recycled glass (around 38%). A small part, of around 8%, is not recycled, but most (54%) is unclear. This makes it difficult to make reliable assumptions about the recycling of this glass colour. The chemical data are so diverse that it is not possible to say something decisive about the changes through time.

The group ‘other’ colours is the smallest (16 samples). Although the largest part is unclear (56%), the group contains more recycled glass (31%) than not recycled glass (13%). P1 contains no recycled samples and P3 and P4 contain only recycled and unclear samples. Lastly, the colours cobalt blue, yellow-green (himt) and purple are only present in P4 and few in numbers. Therefore, it is not possible to make a comparison through time for these colours. It is unclear if the purple glass is recycled, the recycling of yellow-green (himt) coloured glass differs (15% not recycled, 31% recycled and 54% unclear) and from the cobalt blue glass 33% is recycled and 67% is unclear.

Table 5.6: Overview of the totals of the different glass colours, in amount of samples and percentages.

Colour	No	No%	Yes	Yes%	?	?%	Amount of samples
Colourless	47	46,5	24	23,8	30	29,7	101
Green	13	21	23	37,1	26	41,9	62
Aqua/blue	3	7,7	15	38,5	21	53,8	39
Cobalt blue	0	0	3	33,3	6	66,7	9
Yellow-green	2	15,4	4	30,8	7	53,8	13
Purple	0	0	0	0	3	100	3
Other	2	12,5	5	31,3	9	56,2	16
Total	**67**	**27,5%**	**74**	**30,5%**	**102**	**42%**	**243 (100%)**

Recycled, unrecycled and samples from which recycling is unclear appear in all the different colours that occur in the dataset. Except for the colours cobalt blue and purple, which only appear in recycled glass and samples from which recycling is unclear (table 5.6). The colour of glass does not seem to have played a significant part in the decision to recycle glass or not. Overall, samples made from colourless glass are mostly unrecycled and samples made from green, blue and other coloured glass are mainly recycled.

Recycling and provenance

Recycling is a factor that complicates provenance determination. It can make the signature of primary glass sources hard to distinguish and causes mixed signatures in a sample. To link a glass sample to one primary production centre or provenance with full certainty, only samples made from original, unrecycled glass may be used. All provenance groups in this research contain recycled and unrecycled glass and samples for which this is unclear (table 5.7 and appendix 1).

From the 79 samples with a Syro-Palestine provenance 19% (15 samples) is not recycled, 39% (31 samples) is recycled and 42% (33 samples) is unclear. Except for P2, the amount of unrecycled samples lies between the 11-14% through time. P2 tops this by far, in which 55% of the samples are not recycled for certain. Furthermore, P3 and P4 are the periods that contain the highest amount of recycled samples (50% and 40%). Followed by 33% recycling in P2 and 11% in P1. The amount of samples for which recycling is unclear is fluctuating through time (from 11% in P2 to 77% in P1). Overall, the amount of Syro-Palestine glass that has been recycled seems to increase through time.

From the 82 samples with a provenance Egypt Alexandria 48% (39 samples) is not recycled, 19% (16 samples) is recycled and for 33% (27 samples) this is unclear. From this, it can be concluded that the glass was mainly produced in primary production centres from raw materials. A smaller part of the glass is recycled and probably mixed at secondary production places. Through time, the amount of samples for which recycling is known decreases. Both the unrecycled and recycled group decline and the unclear group increases (from 8% in P1 to 40% in P4). The amount of unrecycled glass stretches from 57% in P2 to 44% in P4. The amount of recycled glass lies between the 38% in P1 and 12% in P3.

The 45 samples with provenance Egypt HIMT are not recycled for 18% (8 samples), recycled for 27% (12 samples) and recycling is unclear for 55% (25 samples). This glass provenance does (almost) not occur in the earlier periods, only in P4. Therefore, no visible changes through time can be determined. No certain assumptions can be made, but it seems likely the HIMT glass was more often produced with recycled glass than not. In P4, the main period which contains HIMT glass, 23% of the 35 samples is not recycled, 26% is recycled and 51% unclear.

The 7 glass samples with a west Mediterranean provenance are recycled for 43% (3 samples) and recycling is unclear of 57% (4 samples). The group contains no unrecycled samples. All the samples are placed in P1 and P2, so no dependable comparison through time is possible. Although it can be concluded that glass with a west Mediterrenean provenance of Sagalassos is mostly made from recycled glass, there is too few chemical data to make this statement or further assumptions about recycling in this provenance group reliable.

From the 30 samples classified in the Unknown group, 17% (5 samples) is unrecycled, 40% (12 samples) is recycled and for 43% (13 samples) this is unclear. Most of the recycled samples are dated in P3 and P4. The chemical data are variable through time and it is therefore hard to state something about the change between the different time periods. However, it is clear that a much larger part of the samples with an unknown provenance are made of recycled glass than of unrecycled glass.

Overall, in almost all the provenance groups the unclear recycling group is the largest. When recycling of the different groups is compared, the group Egypt Alexandria contains the most unrecycled samples (47.6%) and the provenance west Mediterrenean the least (0%). From the other three groups 16-19% in not recycled. The amount of recycled samples is almost similar in three groups, west Mediterrenean (42.9%), Unknown (40%) and Syro-Palestine (39.2%). These groups are followed by Egypt HIMT glass with 26.7% and glass from Egypt Alexandria with 19.5% of certain recycling. To summarize, the main part of Syro-Palestine glass is recycled, the group Egypt Alexandria contains predominantly unrecycled samples, glass with an origin in Egypt HIMT is slightly more often recycled than not and samples from the west Mediterrenean and the Unknown group are mostly recycled (table 5.7).

Table 5.7: Overview of the total recycling for each provenance, in amount of samples and percentages.

Provenance	No	No%	Yes	Yes%	?	?%	Amount of samples
Syro-Palestine	15	19%	31	39,2%	33	41,8%	79
Egypt HIMT	8	17,8%	12	26,7%	25	55,5%	45
Egypt Alexandria	39	47,6%	16	19,5%	27	32,9%	82
West Mediterrenean	0	0%	3	42,9%	4	57,1%	7
Unknown	5	16,7%	12	40%	13	43,3%	30
Total	**67**	**27,5%**	**74**	**30,5%**	**102**	**42%**	**243**

5.3 Lead isotope analysis

There are 28 different samples for which lead isotope data is available. 7 of these samples are from glass chunks and 21 from vessels/windows. Besides lead isotope ratios, the lead content is known for 16 of the samples. The lead isotope data is first discussed in general in section 5.2.1 and subsequently into more detail in the following sections.

5.3.1 General overview

Lead isotopes are calculated as a set of three isotope ratios (Pollard and Bray 2015, 998), therefore the main focus of this analysis is on the data from the isotope ratios ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb. These ratios are commonly used in geological research. The isotope ratios ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb are the most common manner to report lead isotope ratios in archaeological research (Artioli 2010, 326).

As a start, a division between the lead isotope ratios was made to indicate differences between the ratios. However, the differences in and between the ratios turned out to be small (table 4.7 and 5.8) and the ranges in which they were divided were close to each other. Therefore, this classification into several ranges of a lead isotope ratio did not prove to be useful. In general, most samples have very similar isotopic values that are on average 18,589, 15,675, 38,673, 0,843 and 2,080. There are a few samples with much lower or higher lead isotope ratios. Due to these samples, the difference in each ratio sometimes seems large and it can cause a distorted view of the average isotope ratio of the main group of samples. Two samples, SA98JP13 and 586, are striking, because the first is responsible for the lowest ^{206}Pb/^{204}Pb ratio and the highest ^{207}Pb/^{204}Pb, ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb ratios and the second sample for the lowest ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb ratios and the highest ^{206}Pb/^{204}Pb ratio.

In comparison with other areas in the Mediterranean and Europe, the differences between the lead isotope ratios of this research are not very unusual (table 5.8 and appendix 2). The overall range of the isotope ratio ^{206}Pb/^{204}Pb is between 18,167 and 18,859, the largest difference between ratios in this research. In this ratio, samples with the provenance Egypt HIMT often have high ratios. The overall range of the isotope ratio ^{207}Pb/^{204}Pb is between 15,632 and 15,728. When this isotope ratio is looked at in detail, the ratio seems to be mixed, with broadly varying provenance, colour and time period. However, when zoomed out just a little, it becomes clear that the range of this ratio is very narrow. The normal differences between provenance, colour and period therefore seem mixed, but actually the samples are quite similar. The overall range of the isotope ratio ^{208}Pb/^{204}Pb is between 38,407 and 38,881. Again, samples with an origin in Egypt HIMT frequently have high ratios.

The overall range of the isotope ratio ^{207}Pb/^{206}Pb is between 0,831 and 0,865. This ratio seems to be quite stable with 18 samples in ranges between 0,840 and 0,849. The overall range of the isotope ratio ^{208}Pb/^{206}Pb is between 2,054 and 2,125 and also seems very stable, with 22 samples in ranges between 2,066 and 2,089. Although the overall range seems small in comparison with the ^{206}Pb/^{204}Pb, ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratio, it encompasses a significant part of the known ^{208}Pb/^{206}Pb ratios for lead sources in the Mediterranean. The ratios vary so widely, because, as mentioned before, some samples have higher or lower ratios than most samples. An explanation for these different lead isotope signatures can be that the source of the lead in these samples perhaps originates in a different area than that of most samples.

Table 5.8: Overall minimum and maximum lead isotope ratios and the difference, of 28 glass samples from Sagalassos.

	^{206}Pb/^{204}Pb	**^{207}Pb/^{204}Pb**	**^{208}Pb/^{204}Pb**	**^{207}Pb/^{206}Pb**	**^{208}Pb/^{206}Pb**
Minimum	18,167	15,632	38,407	0,831	2,054
Maximum	18,859	15,728	38,881	0,865	2,125
Difference	0,692	0,096	0,474	0,034	0,071

Combination of lead and lead isotopes

There are 16 samples for which, besides the lead isotope calculations, the lead content in ppm was measured. These chemical lead values range between 5 and 214 ppm (table 4.8). All the recycled (6 samples) and unrecycled (7 samples) samples from the 28 samples have measurements/calculations of both values. Besides that, there are 3 samples with both values for which recycling is unclear.

To interpret the lead isotopic ratios in a different way, a combination of the chemical lead content and lead isotope ratios has been used to make diagrams of the available data (fig. 5.1 and 5.2). This has been done according to the approach described in Bray *et al.* (2015) and Pollard and Bray (2015). In this approach, the lead chemical concentration is plotted against each isotope ratio, which results in a set of three diagrams. These diagrams are useful because they show the difference between lead isotope ratios in a visual manner and clearer than only data in a table would do. For example, mixing lines or mixed lead isotope signatures will be easier to spot. The plots also give the opportunity to compare the different lead isotope ratios and the chemical lead content with each other.

A mixing line or model can sometimes be recognized in glass made from a combination of different types of (recycled) glass. This mixing can also be observed in the lead isotope and chemical composition of the glass. Due to this mixing of glass, samples regularly contain values/ratios that cannot be linked to one specific aspect, but to two or more aspects. Like, several options for the original provenance, colour or lead isotope ratio of the glass.

In the following sections the observations made about the lead isotope ratios from the tables are combined with those of the diagrams and discussed together. Rather than use them as separate research aspects, their conclusions can complement each other in this way.

5.3.2 Time periods

There are samples with lead and lead isotope data that date in P1, P3 and P4. The samples that date in P1 mainly have the same lead isotopic values. Conversely, those from P4 have broader lead isotopic ratios. In each time period, one to three samples differ from the average ratios, which explains the sometimes large differences in lead isotope ratios that can be observed in table 5.9. Looking at the plots (fig. 5.1), it becomes apparent that the samples from P1 mainly have lower lead isotope ratios than those from P4 for the ratios ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb. For the ratios ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb this is the opposite, there the ratios from P1 are primarily higher than the ratios from P4. There is only one sample in the plots and two in the table that date in P3, therefore only a few reliable observations can be made about these two samples. The lead isotope ratios of both samples are quite similar and comparable with the average ratios of the samples from P4.

The different isotope ratios for P1 and P4 indicate that over time they have increased or decreased, depending on the kind of ratio. One reason for this can be that raw materials from different sources and places were used in different times.

Primary workshops were known to use a wide range of raw materials through time, which can possibly explain some differences in lead isotope ratios (Degryse *et al.* 2005, 296). Another explanation of why the ratios differ might be a different intensity of glass mixing in each period. The glass used for recycling can have had many different silica raw materials with various lead isotope ratios. Like the glass, the ratios would have been mixed, which led to ratios that are the average of the original isotopic compositions (Degryse *et al.* 2005, 296) and these could be higher or lower than those from a different time period.

Table 5.9: The difference between each minimum and maximum lead isotope ratio, for all the time periods.

Period	**Samples**	**^{206}Pb/^{204}Pb**	**^{207}Pb/^{204}Pb**	**^{208}Pb/^{204}Pb**	**^{207}Pb/^{206}Pb**	**^{208}Pb/^{206}Pb**
1	7	0,138	0,079	0,345	0,006	0,009
3	2	0,078	0,015	0,178	0,002	0,001
4	19	0,692	0,078	0,303	0,034	0,071

5.3.3 Colours

With 10 samples, blue coloured glass is the largest colour group. Furthermore, 6 samples are colourless, 6 green and 5 yellow-green (typical himt colour) (table 4.4 and 5.10). One sample with a cobalt blue colour is left out of the table and plots, because it could not be compared with other samples of the same colour and its lead content is unknown. Most of the lead isotope ratios of the colourless and of the blue and yellow-green coloured glass are close to each other (table 5.10 and fig. 5.1). The ratios are narrow, which indicates that the different samples of each colour are quite similar. The glass has a homogeneous lead isotope composition, which suggests that only a few different, but homogeneous, silica raw materials were used for the glass production (Degryse and Braekmans 2014, 201; Degryse *et al.* 2005, 295).

The lead isotopic ratios of the green glass varies more than those of the other colours (table 5.10 and fig. 5.1). This larger difference in ratios indicates that the lead isotope composition of the green glass is heterogeneous and multiple sources of raw materials were possibly used in the manufacture of this glass. Moreover, the mixing of multiple (sand) raw materials is a strong indication for recycling (Degryse and Braekmans 2014, 201; Degryse *et al.* 2005, 295). Except for the ratio

^{208}Pb/^{206}Pb, the diagrams seem to confirm the conclusion from the table that the samples of green glass are heterogeneous in lead isotopic composition (fig. 5.1).

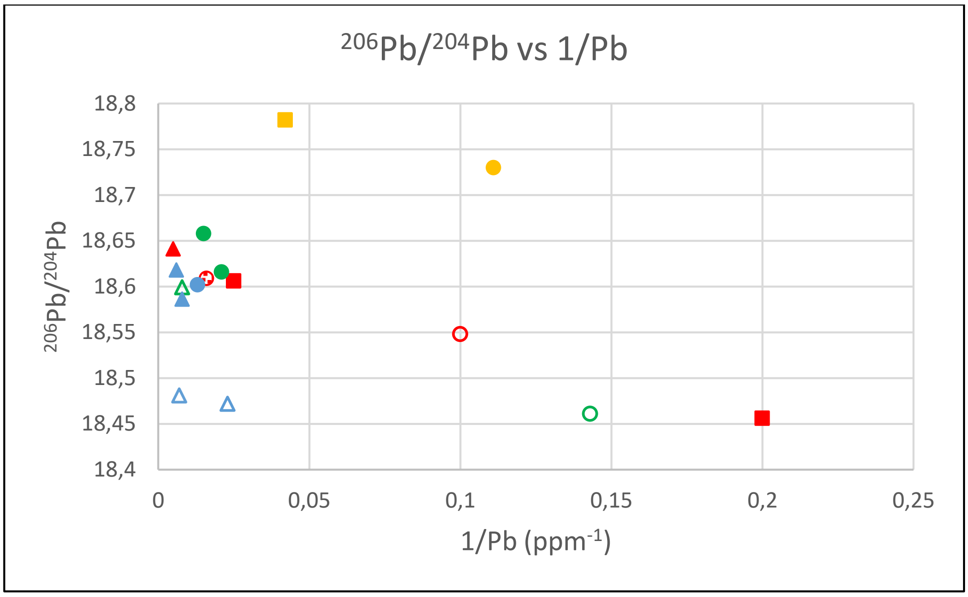
In Degryse *et al.* (2005, 295, 297) the 6 colourless samples of this research are also discussed and the lead isotopic composition is argued to be heterogeneous. However, in this research, in comparison with the available data, it is argued that the colourless glass has a homogeneous composition. Although the differences of the ratios ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb are considerable, the other three known isotopic ratios are very narrow.

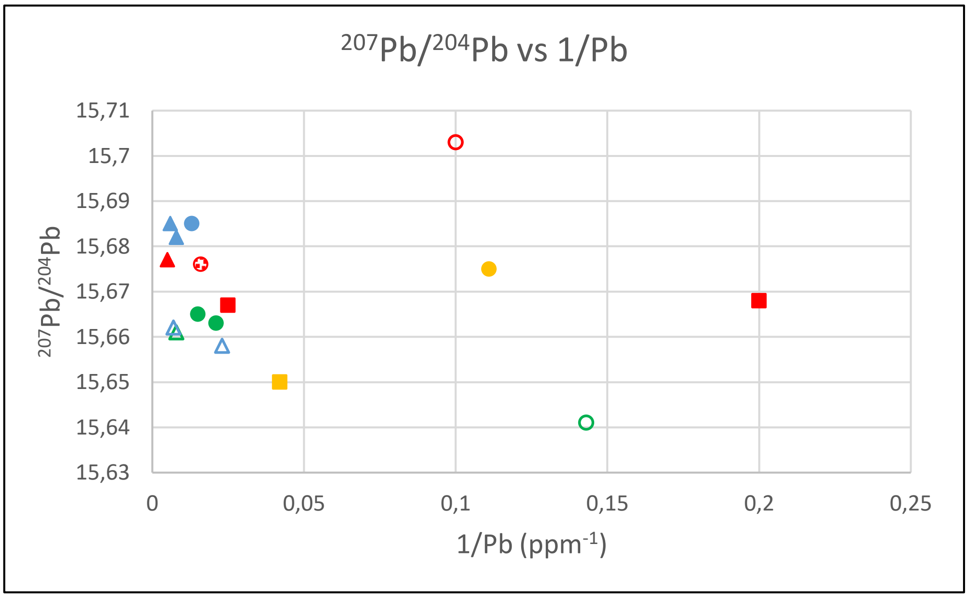
Table 5.10: The difference between each minimum and maximum lead isotope ratio, for all the colours.

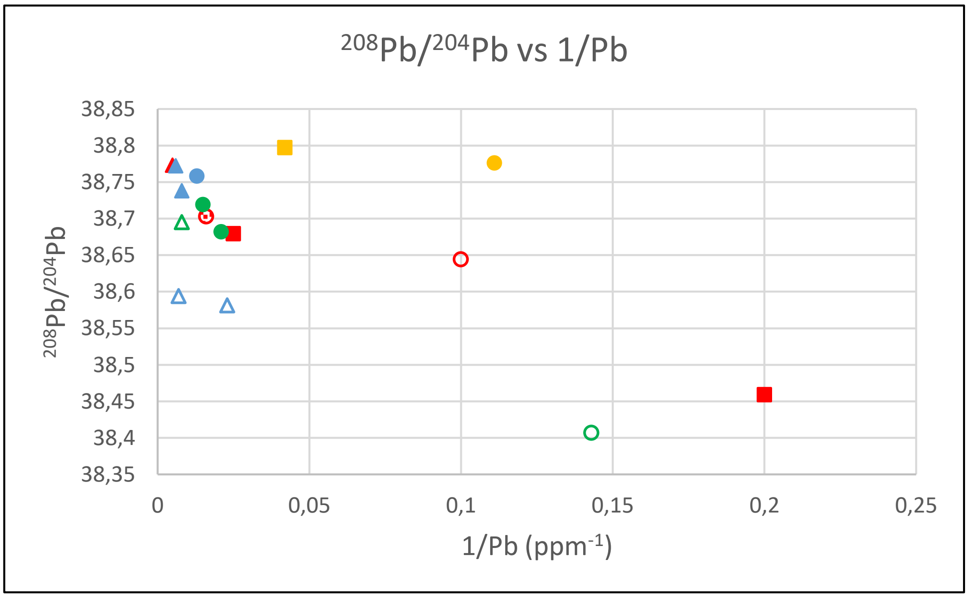
Colour	**Samples**	**^{206}Pb/^{204}Pb**	**^{207}Pb/^{204}Pb**	**^{208}Pb/^{204}Pb**	**^{207}Pb/^{206}Pb**	**^{208}Pb/^{206}Pb**
Blue/aqua	10	0,146	0,079	0,278	0,006	0,011
Colourless	6	0,231	0,036	0,422	0,009	0,005
Green	6	0,572	0,087	0,331	0,028	0,058
Yellow-green	5	0,186	0,069	0,065	0,011	0,023

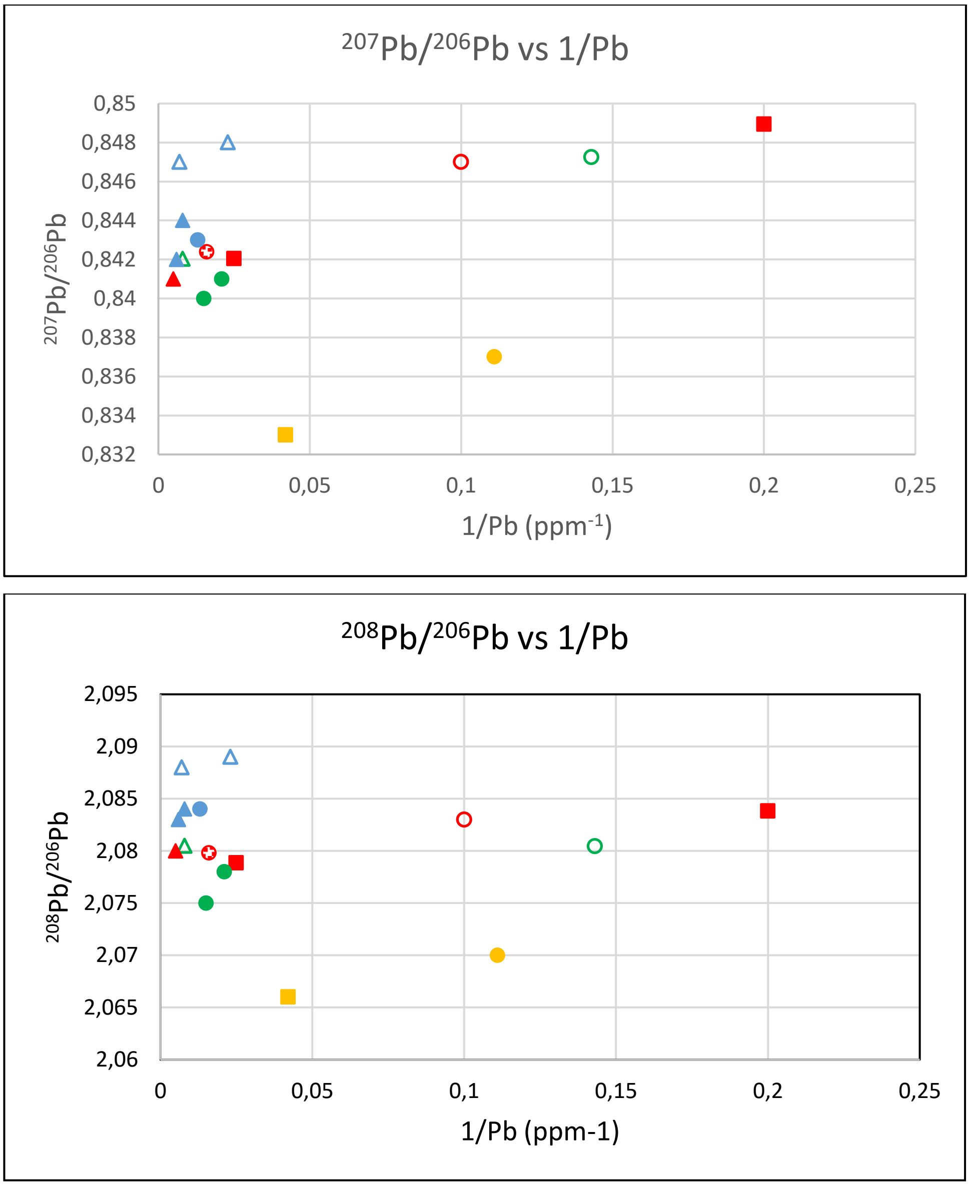
The 5 blue samples in the diagrams are mostly grouped together. Two are slightly deviant from the other three, but this is only clearly visible in the ratio ^{206}Pb/^{204}Pb. The blue colour group contains the most (certain) recycled samples, which is striking, because the lead isotope composition is quite homogeneous. Since the green glass has a heterogeneous lead isotope composition, this colour group was expected to contain the most recycled samples.

Looking at the diagrams, it becomes clear that 3 samples often differentiate from most of the other lead isotope ratios and thus make the range of each ratio wider. This is for example clearly visible for the colourless glass. The ratios of 4 samples are quite narrow, but a fifth sample deviates from this and increases the overall range of the ratios. This is less clear for the two yellow-green coloured samples. Although there are sometimes clearly visible differences between the ratios of the two samples, in general they are quite similar. The samples of this colour often have higher (^{206}Pb/^{204}Pb, ^{208}Pb/^{204}Pb ratio) or lower (^{207}Pb/^{206}Pb, ^{208}Pb/^{206}Pb ratio) lead isotope ratios than the other colours.


^{206}Pb/^{204}Pb vs 1/Pb
^{206}Pb/^{204}Pb
18,8
18,75
18,7
18,65
18,6
18,55
18,5
18,45
18,4
0
0,05
0,1
0,15
0,2
0,25
1/Pb (ppm^{-1})


^{207}Pb/^{204}Pb vs 1/Pb
^{207}Pb/^{204}Pb
15,71
15,7
15,69
15,68
15,67
15,66
15,65
15,64
15,63
0
0,05
0,1
0,15
0,2
0,25
1/Pb (ppm^{-1})


^{208}Pb/^{204}Pb vs 1/Pb
^{208}Pb/^{204}Pb
38,85
38,8
38,75
38,7
38,65
38,6
38,55
38,5
38,45
38,4
38,35
0
0,05
0,1
0,15
0,2
0,25
1/Pb (ppm^{-1})



Legend

No fill: P1

Dot fill: P3

Complete fill: P4

□ Recycling unclear

○ Not recycled

∆ Recycled

Aqua/Blue

Colourless

Green

Yellow-green (himt)

Figure 5.1: A set of three and two additional diagrams, plotting 1/Pb against the isotope ratios ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb, ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb of 16 glass samples from Sagalassos. Time period, glass colour and recycling are indicated for each sample.

It is difficult to define clear mixing lines based on the glass colours of the samples, because there are only 16 samples in the diagrams, which is not that many. A possibility might be the mixing of yellow-green and blue glass to make green and/or colourless glass. However, this mixing trend is only clearly visible in the ratios $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$.

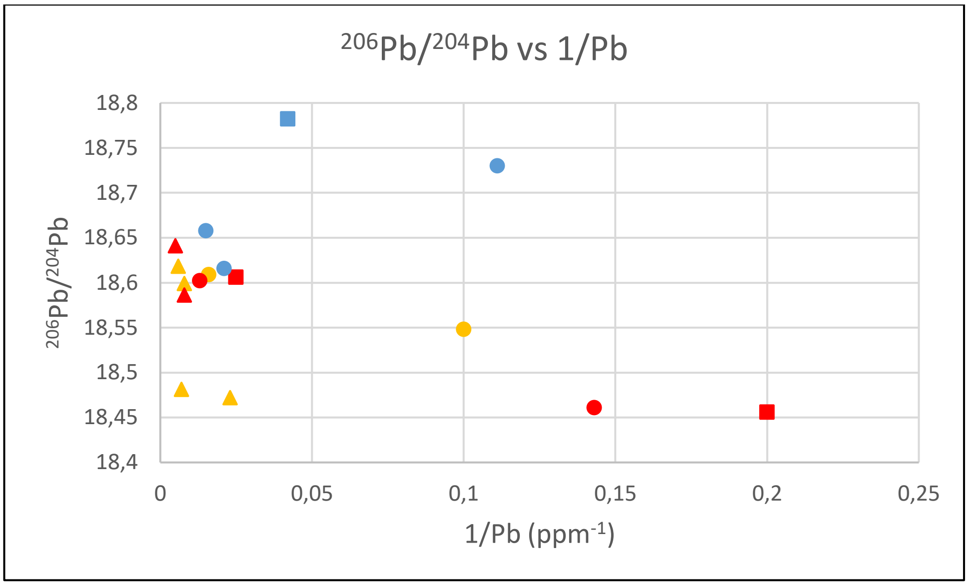
5.3.4 Provenance

There are 10 samples with provenance Egypt Alexandria, 8 with Syro-Palestine and 9 with Egypt HIMT. One sample with an unknown origin is left out of the table and plots, because it cannot be compared with samples from the same provenance and the lead content is not known. Based on the data in table 5.11, it can be concluded that the glass from Egypt Alexandria and Syro-Palestine is mainly homogeneous in lead isotope composition and the glass with a provenance Egypt HIMT heterogeneous. This cannot be observed so clearly when looking at the diagrams (fig. 5.2). In the ratios $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ 1 to 2 samples with the provenance Egypt Alexandria and Syro-Palestine deviate from the average ratios, which is demonstrated by a rather wide range of these ratios. Due to unknown chemical lead values, not all samples that are in the table are in the diagrams. This can sometimes lead to a distorted view, which explains why the glass from Egypt HIMT looks more homogeneous in some diagrams than the glass from Egypt Alexandria and Syro-Palestine.

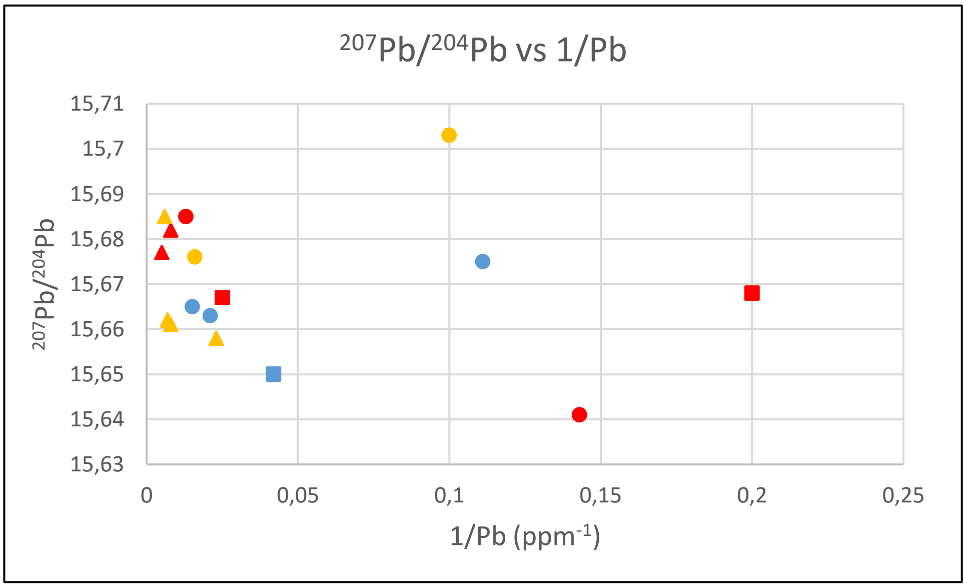
Table 5.11: The difference between each minimum and maximum lead isotope ratio, for all the provenance groups.

Provenance	**Samples**	**$^{206}Pb/^{204}Pb$**	**$^{207}Pb/^{204}Pb$**	**$^{208}Pb/^{204}Pb$**	**$^{207}Pb/^{206}Pb$**	**$^{208}Pb/^{206}Pb$**
Egypt Alexandria	10	0,215	0,045	0,328	0,008	0,011
Syro-Palestine	8	0,185	0,079	0,366	0,008	0,005
Egypt HIMT	9	0,692	0,078	0,187	0,034	0,071

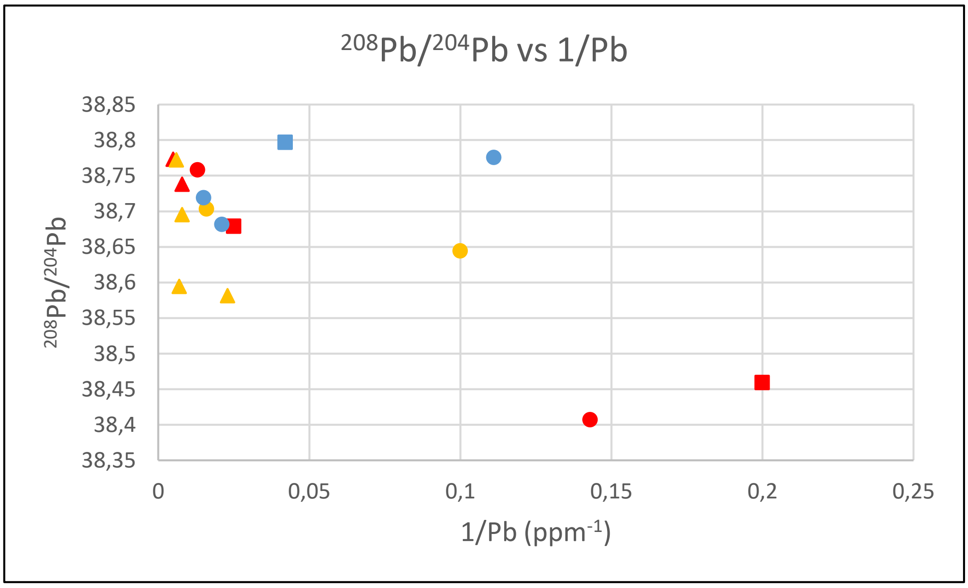
The lead isotope ratios of the samples with provenance Egypt Alexandria and Syro-Palestine are often very similar. This confirms again, certainly in combination with the chemical data (section 5.1), that the glass from these two provenance groups have a very similar composition, except for the clear difference in alumina content. In the ratio $^{206}Pb/^{204}Pb$ these two provenances have lower ratios and glass from Egypt HIMT higher. For the ratios $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ the 3 groups have similar lead isotope values and in the ratios $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ Egypt HIMT has the lowest ratios and Egypt Alexandria and Syro-Palestine the highest.



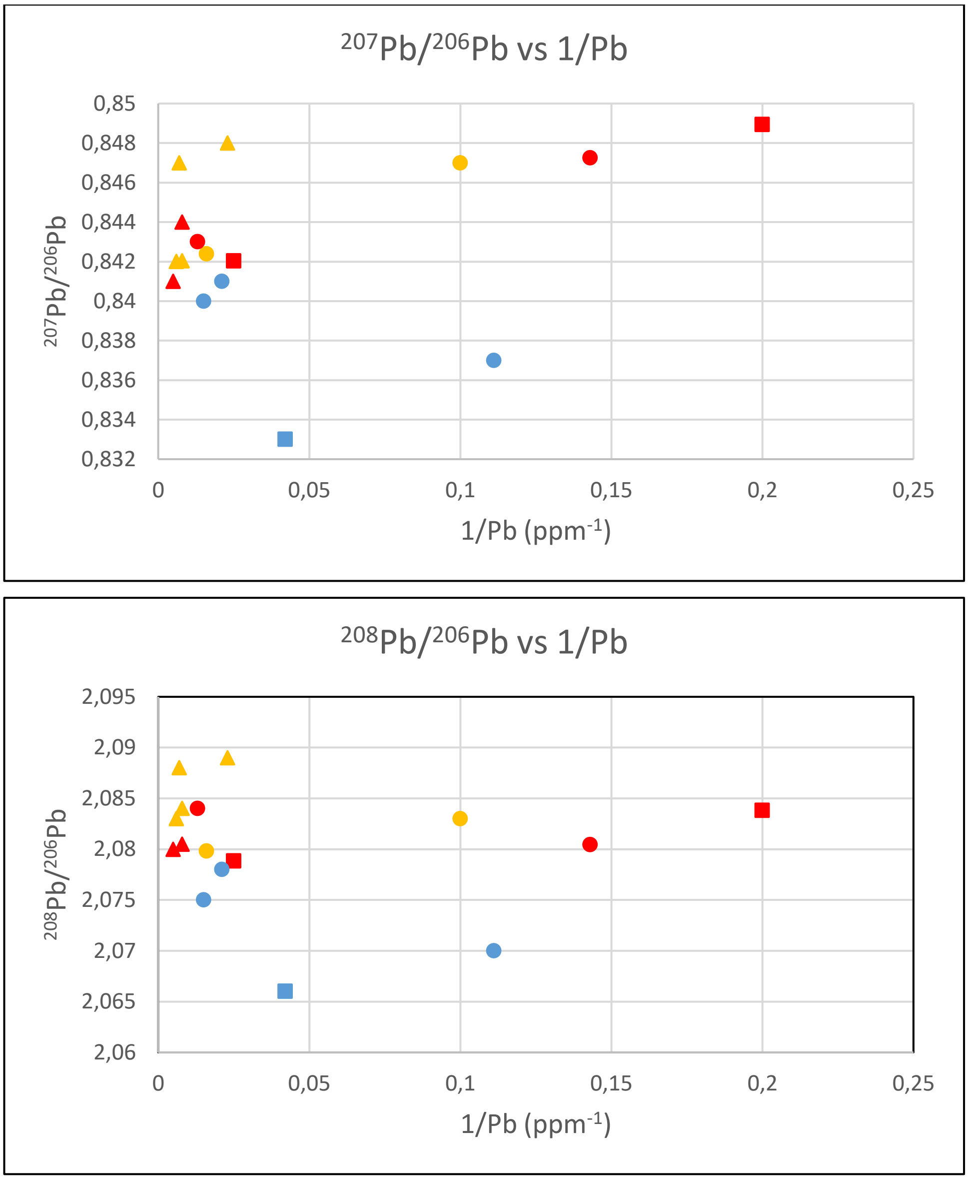
$^{206}Pb/^{204}Pb$ vs 1/Pb



$^{207}Pb/^{204}Pb$ vs 1/Pb



$^{208}Pb/^{204}Pb$ vs 1/Pb



Legend

Egypt Alexandria
Syro-Palestine
Egypt HIMT

□ Recycling unclear
○ Not recycled
∆ Recycled

Figure 5.2: A set of three and two additional diagrams, plotting 1/Pb against the isotope ratios ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb, ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb of 16 glass samples from Sagalassos. Provenance and recycling are indicated for each sample.

Glass from Egypt Alexandria and Syro-Palestine was probably produced with raw materials from only a few sand sources or with the use of sands that originate in areas with the same or a similar geological signature. For the production of glass from Egypt HIMT it is likely that raw materials from many different or heterogeneous sand sources were used. Moreover, no clear mixing trends could be observed in the diagrams of fig. 5.2, which makes it plausible that glass from this three different provenance areas were not very often mixed with each other.

5.3.5 Recycling

In this section the lead isotope ratios of the recycled and unrecycled samples are compared to determine what kind of effect recycling has on lead isotope values. There are 7 unrecycled, 6 recycled and 15 recycling unclear samples of which lead isotope data is known (table 5.12). Since the samples for which recycling in unclear are difficult to use in this comparison and the chemical lead content is only known for 3 of the 15 samples, this group is not discussed into detail. It is a very mixed group and contains all the lowest and highest lead isotope ratios of the 28 samples, except for the lowest ^{208}Pb/^{204}Pb ratio. Therefore, the range of the ratios is broad and the lead isotope composition heterogeneous.

Table 5.12: The difference between each minimum and maximum lead isotope ratio, for the recycled and unrecycled samples and for the samples for which this is unclear.

	Samples	**^{206}Pb/^{204}Pb**	**^{207}Pb/^{204}Pb**	**^{208}Pb/^{204}Pb**	**^{207}Pb/^{206}Pb**	**^{208}Pb/^{206}Pb**
Recycled	6	0,169	0,027	0,192	0,007	0,009
Unrecycled	7	0,269	0,062	0,369	0,006	0,014
Unclear	15	0,692	0,096	0,422	0,034	0,071

Unrecycled samples

Of the 7 unrecycled samples, 2 have the provenance Syro-Palestine, 2 Egypt Alexandria and 3 Egypt HIMT (table 5.13). The lead isotope ratios of the unrecycled glass are more diverse than those of recycled glass. They mainly concern middle to higher lead isotopic values for the ratios ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb. Conversely, they mostly have lower to middle lead isotopic values for the ratios ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb. The differences in the lead isotope ratios, between each provenance and in each provenance, are relatively small, expect for one sample. This sample has the lowest isotopic value of the ^{208}Pb/^{204}Pb ratio of all the 28 samples. Because of this, when looking at the data (table 5.12, 5.13 and fig. 5.2), it seems the lead isotope composition of the unrecycled glass is not really homogeneous or heterogeneous, but in between.

Where recycled samples have often clustered middle to higher lead isotope ratios in the diagrams, the ratios of unrecycled samples are more scattered. It seems that unrecycled glass more frequently has low or high lead isotope ratios than average ratios. The samples in the diagrams with provenance Egypt HIMT are probably all 4 not recycled. It is different for the green coloured glass, both recycled and unrecycled samples have mostly middle ratios. Apart from one sample, which has much lower or higher ratios than the other green samples. This aligns with the overall view of unrecycled glass. It is more similar than different, taken into account that there are 1 to 3 samples in each ratio that deviate and make the entire ratio much wider. Furthermore, there is no clear difference in lead isotope ratios between the different provenance groups of the unrecycled samples.

Table 5.13: Lead isotope ratios of all the unrecycled samples, a total of 7 samples. Divided in provenance groups (EA=Egypt Alexandria, SP= Syro-Palestine, HIMT= Egypt HIMT).

Provenance	**Sample**	**Period**	**Pb (ppm)**	**^{206}Pb/ ^{204}Pb**	**^{207}Pb/ ^{204}Pb**	**^{208}Pb/ ^{204}Pb**	**^{207}Pb/ ^{206}Pb**	**^{208}Pb/ ^{206}Pb**
EA	574	1	10	18,548	15,703	38,644	0,847	2,083
EA	579	3	61	18,609	15,676	38,703	0,842	2,080
SP	582	4	80	18,602	15,685	38,758	0,843	2,084
SP	721	1	7	18,461	15,641	38,407	0,847	2,080
HIMT	720	4	9	18,730	15,675	38,776	0,837	2,070
HIMT	727	4	48	18,616	15,663	38,682	0,841	2,078
HIMT	729	4	66	18,658	15,665	38,719	0,840	2,075

Table 5.14: Lead isotope values of all the recycled samples, a total of 6 samples. Divided in provenance groups (EA=Egypt Alexandria and SP= Syro-Palestine).

Provenance	**Sample**	**Period**	**Pb (ppm)**	**^{206}Pb/ ^{204}Pb**	**^{207}Pb/ ^{204}Pb**	**^{208}Pb/ ^{204}Pb**	**^{207}Pb/ ^{206}Pb**	**^{208}Pb/ ^{206}Pb**
EA	572	1	44	18,472	15,658	38,581	0,848	2,089
EA	577	1	143	18,481	15,662	38,594	0,847	2,088
EA	590	4	160	18,618	15,685	38,772	0,842	2,083
EA	723	1	130	18,599	15,661	38,695	0,842	2,080
SP	583	4	123	18,586	15,682	38,738	0,844	2,084
SP	594	4	214	18,641	15,677	38,773	0,841	2,080

Recycled samples

Of the 6 recycled samples, 2 have a provenance in Syro-Palestine and 4 in Egypt Alexandria (table 5.14). In general, there are only relatively small to no differences in the lead isotopic values, which mostly have middle to higher ratios. They are quite close in all the ratios and the lead isotope composition is homogeneous.

Of all the different colours, blue glass contains the most recycled samples. The middle to high ratios of the samples are close together. On the other hand, recycling does not seems to have a significant effect on colourless glass. There are at least one recycled and one unrecycled sample that always have similar lead isotope values.

In the diagrams (fig. 5.2) it is clearly visible that the recycled samples have a higher chemical lead content (in ppm) than the unrecycled and unclear samples. This is related to the recycling of glass, for which a raised lead level is an indicator. The lead content from different glass used for recycling is combined, which can cause an increased lead level in recycled glass.

It seems that glass with the provenance Egypt Alexandria was mostly recycled in P1 and not that frequent in later periods. This provenance group also contains the most (certain) recycled samples. This is striking, because the lead isotope composition is quite homogeneous, which is also the case for blue coloured glass samples (section 5.3.3). Recycled glass is thus often homogeneous in lead isotope composition. It was expected that recycled glass would mainly be heterogeneous, because of the wide variety of glass compositions that can be combined in this manner. However, looking at the diagrams (fig. 5.1 and 5.2) it makes more sense that recycled samples have a homogeneous instead of a heterogeneous lead isotope composition. During recycling, different lead isotope signatures are mixed with each other, which will rather bring them and the average ratio of the samples closer together than widen the entire range.

Overall, it seems that the effect of recycling on lead isotope ratios is that they close in on each other, the differences between them get smaller and thus the lead isotope composition becomes more homogeneous.

5.3.6 Roman lead sources

In this section the lead isotope ratios of the 6 recycled samples are compared with other known lead isotopic ratios in the Mediterranean and Europe in order to determine the possible sources or mines from which the lead in the glass samples from Sagalassos originates.

The Romans had access to a wide variety of ore deposits in the ancient world. The most important region for the obtainment of lead was the Iberian Peninsula (present-day Spain), with the districts Cartagena–Mazzarón and Sierra Morena (Bode, Hauptmann and Mezger 2009, 183; Trincherini *et al.* 2010). Since this is a long way from Sagalassos and there were many lead sources available at that time, data from a large area has been obtained to compare with the lead isotope ratios from the Sagalassos glass samples (appendix 2).

To make the comparison, a considerable amount of available lead isotope data from literature and a digital database was collected in an Excel document and large table in Word (appendix 2). This data usually consisted of two or three isotope ratios and sometimes of five. It was copied from literature into the Excel document, in which the samples of each location or lead source got their own sheet, leading to a document with 14 sheets. Subsequently, the isotopic values of all the samples of each source were used to calculate the average ratios of the ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb, ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb ratios of that lead source. The average lead isotope ratios of the Sagalassos glass were also calculated and all these average values were recorded in the table. The table has 9 different fields; area, objects/context, time, ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb, ^{207}Pb/^{206}Pb, ^{208}Pb/^{206}Pb and literature. The average values were mostly calculated from samples coming from one country or large region. Besides the average isotope ratios, the known minimum ratio, maximum ratio and the difference between them of a group of samples were also documented. When average lead isotope ratios were given in literature or only one or two samples were known from a source, this data was immediately documented in the table instead of in the Excel document. After making the table as complete as possible, containing 34 different sources, mostly countries, it was used to compare the data. The table proofed only useful for a general comparison. The average, minimum and maximum ratios of countries were compared with the ratios from the Sagalassos glass. Additionally, an overview was made of the average, minimum and maximum lead isotope ratios of all the samples together, combining data of many lead sources spread across

Europe and the Mediterrenean area. The differences between the ratios in this overview turned out to be considerable and could not provide additional information that was useful for the comparison. Next, a more detailed comparison of the most likely sources was made using again the data in the Excel document. Countries from which hundreds of samples were known were now looked at on a regional and/or site level. Also, not only the average ratios were taken into account, but the ratios of each separate sample. In this way the following comparison could be made.

When lead isotopic data is used in archaeology to determine provenance, there are some considerations to keep in mind, which are not always taken into account in literature. For starters, it is possible for one ore deposit to be represented by a wide range of lead isotope ratios. Conversely, two or more ore sources from different geographical areas can have overlapping lead isotopic signatures (Baron *et al.* 2014, 667). Besides that, numerous samples need to be taken from an ore deposit to obtain a representative overview of a source. Additionally, the geological context of a source should be considered in order to collect samples with archaeological significance (Baron *et al.* 2014, 669, 670). Because not all literature used in this comparison considers all of these aspects, care should be taken with the conclusions that are drawn from it.

After comparing all the data, there could not be found one source in literature that had exactly the same lead isotope signature as the glass from Sagalassos. Greece, Germany, Israel and Egypt were ruled out (Bode, Hauptmann and Mezger 2009; Klein *et al.* 2004; Klein *et al.* 2010; Stos-Gale *et al.* 1996; Wolf *et al.* 2003, 412; http://oxalid.arch.ox.ac.uk). Subsequently, large areas of the British Isles, Spain, Italy and Turkey were rejected as likely area of the leads origin (Huelga-Suarez *et al.* 2012, 693; Klein *et al.* 2004; Müller *et al.* 2015, 475, 476; Rohl 1996; Yener *et al.* 1991, 560, 561; Zalduegui *et al.* 2004; http://oxalid.arch.ox.ac.uk). Finally, some areas with similar lead isotope signatures as those from the Sagalassos glass remained, they are noted down in table 5.15.

Table 5.15: Overview of lead isotope ratios of different provenance areas, similar, but not exactly the same as the lead isotope ratios of the Sagalassos glass.

Area	**Objects/ context**	**^{206}Pb/ ^{204}Pb**	**^{207}Pb/ ^{204}Pb**	**^{208}Pb/ ^{204}Pb**	**^{207}Pb/ ^{206}Pb**	**^{208}Pb/ ^{206}Pb**	**Literature**
Turkey Sagalassos	4 recycled glass samples with provenance Egypt Alexandria	**18,543**	**15,667**	**38,661**	**0,845**	**2,085**	Own data.
Turkey Sagalassos	2 recycled glass samples with provenance Syro-Palestine	**18,614**	**15,680**	**38,756**	**0,842**	**2,082**	Own data.
France	4 Roman lead ingots Saintes-Maries-de-la-Mer	18,394	15,628	38,375	0,849	2,086	Baron *et al.* 2014, 676.
Bulgaria	9 ores Panagyurski district	18,513	-	-	0,843	2,083	http://oxalid.arch.ox.ac.uk/Bulgaria/Bulgaria.html Stos-Gale *et al.* 1998.
	23 ores North-West Region	18,396	-	-	0,850	2,085	
	11 ores Stara Zagora region	18,491	-	-	0,844	2,082	
Turkey Taurus 2A	12 ore/slag samples	-	-	-	0,841	2,081	Yener *et al.* 1991, 560.
Spain S'Argentera	1 ore with provenance Ibiza	18,670	15,681	38,923	0,840	2,084	Müller *et al.* 2015, 475, 476.
Italy Sardinia	10 ores from the Capo Marargiu (SS) deposit	18,574	-	-	0,843	2,086	http://oxalid.arch.ox.ac.uk/Italy/Italy.html
Cyprus	88 ores Larnaca region	18,614	-	-	0,837	2,074	http://oxalid.arch.ox.ac.uk/Cyprus/Cyprus.html Gale *et al.* 1997.
	40 ores Limni region	18,537	-	-	0,842	2,078	
England	25 ores from Cheshire, Alderley Edge	18,455	-	-	0,847	2,083	http://oxalid.arch.ox.ac.uk/British/British.html Rohl 1996.

Similar lead isotope signatures can be found in seven countries, in ten different regions (table 5.15): Saintes-Maries-de-la-Mer in France, North-West, Panagyurski district and Stara Zagora in Bulgaria, Taurus 2A in Turkey, S'Argentera in Spain (only one ore sample and therefore hardly reliable), Sardinia the Capo Marargiu deposit in Italy, Larnaca and Limni on Cyprus and Cheshire - Alderley Edge in England. The lead isotope signatures of the Panagyurski district in Bulgaria and the Capo Marargiu deposit in Italy (Sardina) are the most similar to the samples with provenance Egypt Alexandria and those from the Capo Marargiu deposit in Italy (Sardina) are most similar to the samples with provenance Syro-Palestine. A side note is that all these regions have similar lead isotope ratios, but are no exact match. Therefore, it could be possible that the lead in the Sagalassos glass does not originate in any of the presented areas.

One explanation for not finding an exact match is that there is no data available about the original lead source(s) of the Sagalassos glass. It can be the case that this data is not published or sampled, but also that the source has not been recovered after use in the Roman time and is currently still unknown. Another explanation is that the lead isotopes in the glass have such a mixed signature, that the original lead source(s) cannot be traced back through them. If this is the case, mixing lines in the glass can possibly be indicated. If these are indicated, they can perhaps help in tracing the original lead source(s). However, no obvious mixing lines could be determined between the areas mentioned in table 5.15. The second explanation is argued to be more likely, because it is already known that the glass is recycled and there are many sources known from literature that are partly the same or similar to the lead isotope ratios of the samples from Sagalassos. If these sources were to be combined, an exact match might be determined.

Overall, only similar lead isotope signatures can be linked to those from the glass samples. The lead in the Sagalassos glass might originate in the Panagyurski district in Bulgaria and/or in the Capo Marargiu deposit in Italy (Sardina).

5.3.7 Conclusion lead isotope analysis

There are 28 samples for which lead isotope ratios are known and for 16 of these the chemical lead content is also known. These 16 samples are presented in diagrams in which the chemical lead content is plotted against the five known lead isotope ratios. Although there are some samples that deviate and make the overall range of the ratios wider, in general the differences in and between the ratios are small. The different isotope ratios for P1 and P4 indicate that over time they have increased or decreased, depending on the kind of ratio. This probably happened because of the use of several raw materials through time. The colourless, blue and yellow-green coloured glass have a homogeneous lead isotope composition and the green glass a heterogeneous one. A potential mixing trend that can be observed is the mixing of yellow-green and blue glass to produce green and/or colourless glass.

The glass with provenance Egypt Alexandria and Syro-Palestine is homogeneous in lead isotope composition, which suggests that only one or a few sand sources were used in its production. The glass samples with an Egypt HIMT provenance are heterogeneous, which indicates the possible use of many different or heterogeneous sand sources in its production. The lead isotope ratios of unrecycled glass are much wider in range than those of the recycled samples. However, they are more similar than different and there is no clear difference in lead isotope values between the provenance groups of the unrecycled samples. The effect of recycling on lead isotope ratios is that they close in on each other and thus their composition becomes more homogeneous. Furthermore, a comparison was made between the lead isotope ratios of the 6 recycled samples and other known lead isotopic values in the Mediterranean and Europe. From this it can be concluded that the lead in the Sagalassos glass might originate in the Panagyurski district in Bulgaria and/or in the Capo Marargiu deposit in Italy (Sardina).

5.4 Combined analysis

In this section the chemical and lead isotope analyses are linked with each other. The interpretations from the provenance, recycling and lead isotope analyses are combined and connected to the concept of flow. In this way, it can be discussed if and in what manner the obtained pieces of information fit into the dynamic system of the changing Sagalassos glass. This information can be seen as snapshots of knowledge in time about the flow of Sagalassos glass in a specific time period. It can help determine parts of the life history of the glass objects, materials or possibly the entire glass flow from the ancient city of Sagalassos.

One way to combine chemical and lead isotope data is already discussed in the former section. In section 5.3, diagrams are presented in which the chemical lead concentration is plotted against each lead isotope ratio. Due to this diagrams, different, more accurate interpretations about the lead isotope data could be made than while using the traditional isotope bi-plots. It is for example easier to spot mixing lines or to spot groups of objects with similar isotopic values, possibly originating from the same source (Pollard and Bray 2015, 1006).

5.4.1 Time period

There is a continuous presence of glass with the provenances Egypt Alexandria and Syro-Palestine through all the time periods. This means that there was an ongoing trade between these areas and Sagalassos, whether direct or indirect. For this to be possible, there probably was a continuous production of glass and a preference of people for this specific glass. On the other hand, the large amount of this glass in comparison with other glass types could also be the result of price and availability. Maybe this glass was the easiest and cheapest to obtain for traders from Sagalassos and could it be seen as the normal glass for people at that time. Furthermore, the total amount of glass from Egypt Alexandria decreases slightly over time, which could indicate some fluctuations in the glass trade.

The recycling of glass through time is quite stable (around 30%) and occurred in all time periods. Besides recycled glass, there also was a stable stream (around 26%) of unrecycled objects in Sagalassos. These objects were not changed since made in a primary production centre and were probably obtained through direct trade. Although the glass from one primary production centre did not differ significantly, the change of the isotope ratios through time indicate that people used several raw materials for the production of the same primary glass over time. Because of some reason, perhaps depletion of sources or distance, people felt the need to look for different sources of raw materials and were able to find and use them. The introduction of glass with the provenance Egypt HIMT in the 4th century AD (P3 and P4) is another example of the resourcefulness of humans. They most likely experimented with glass and raw materials in order to create new types, as for example the typical yellow-green coloured HIMT glass.

Another thing that needs to be mentioned is that because a specific time period is discussed in this research, it will only be possible to determine a part of the life history of the Sagalassos glass. The story of the entire Sagalassos glass flow, especially of the recycled glass, already started before 1 AD and was continued after 700 AD.

5.4.2 Glass colours

Even though there were varying preferences for certain glass colours through time, the colours do not seem to have had significant influence on provenance or the decision to recycle or not. In every provenance group samples from all main colours are present, which is almost the same for recycled and unrecycled glass and samples from which recycling is unclear. Except for the colours cobalt blue and purple. This means that glass in multiple colours was produced at the same primary production centre. Since people took effort to produce different colours of glass, it can be assumed that this was profitable and there was a demand for it. It also underlines the knowledge that people had about colouring glass and how to change the proportions of raw materials or the composition of glass to obtain the desired colour.

Although no exceptions were made in colours for recycling, colourless glass is less frequent recycled than the other colours. Perhaps it was harder to use in recycling or to maintain the desired colour. It is also an option that colourless glass was of higher quality or that people treated it with more care than other glass, therefore it would break less frequent and could not be used as a regular material for recycling. However, colourless glass, and also blue and yellow-green glass, have a homogeneous lead isotope composition, which is usually seen in recycled glass. This seems to be in conflict with the other indications for recycling. Green glass deals with the same problem, the lead isotope composition is heterogeneous, but the glass is recycled for at least 37%. Yet, just because homogeneous glass is often connected with recycling and vice-versa, it does not have to mean that homogeneous glass is always recycled. Maybe the raw materials already had similar lead isotope ratios or the green heterogeneous glass has not been recycled on such a level that the isotopic signatures were notably influenced.

5.4.3 Provenance

Since Egypt Alexandria and Syro-Palestine are the two largest provenance groups, there probably was a good trade network between Sagalassos and Egypt and Syro-Palestine. There are fewer samples with the provenances Egypt HIMT and the west Mediterrenean, most likely because there was less or indirect trade with these areas. The people of Sagalassos might be less interested in this glass, but more plausible is that the distance and time period in which these two glass types could be obtained were the limited factors. West Mediterrenean glass was made until the 5th century AD and Egypt HIMT glass from the 4th century AD onwards. In comparison with the continuous glass production from Egypt Alexandria and Syro-Palestine, it is not a surprise that the presence of these two glass types in Sagalassos was limited. The comparison of lead isotope ratios of samples from Sagalassos with those of known Roman lead sources also suggest that long distance trade, possibly with traders from Bulgaria and/or Italy, was necessary to obtain the lead that is part of some of the Sagalassos glass. Because it is not known where the lead from these sources might be added to glass, it is possible that the lead was already part of the glass when it was imported into Sagalassos and that there was no direct trade between Sagalassos and Bulgaria and/or Italy.

The 20 samples that cannot be related to any known provenance group illustrate two things. One, that recycling can influence the chemical signature of glass and even make it unrecognizable for provenance determination. Two, that there might still be unknown provenance areas of archaeological found primary glass. Taking recycling into account, this was something that happened frequently and for which glass from all provenances was used. Yet, there was a difference in how much glass of a certain provenance was used for recycling. For example, glass from Egypt Alexandria was mostly primary glass and that from the west Mediterrenean was usually recycled. Moreover, the lead isotope composition of the provenances Egypt Alexandria and Syro-Palestine is homogeneous and that of Egypt HIMT heterogeneous. As noted before (section 5.4.2), a homogeneous lead isotope composition can be caused through recycling. However, it would be very strange if this was the case for glass from a primary production centre and other explanations for the homogeneous composition are therefore more likely. Such as the use of only one or a few sand sources for the glass production. If possible, it would have been easier for people to obtain suitable glass making raw materials at one (central) location instead of collecting it from several areas.

5.4.4 Recycling

It is hard to determine recycling or not for all the glass samples, it definitely was a normal habit for glass from Sagalassos. Recycling was not necessarily carried out in Sagalassos, glass could also be imported into Sagalassos in a recycled state. The effect of recycling on lead isotope ratios is that they become more similar and their composition becomes more homogeneous. This can become a problem when a lot of glass is recycled and used over and over again for recycling. Depending on the use and composition of the glass this can happen in for example 20 or 200 years. Due to the constant recycling, the chemical and lead isotope signature shall become very homogeneous and the provenance of the primary glass increasingly difficult to determine. Furthermore, recycling can not only change the composition of glass, but also its use or social meaning. For example, a wine glass used for special dinners is broken, collected as cullet with other broken glass and subsequently recycled into a simple bottle to store liquids. First the object is a luxurious drinking glass to demonstrate wealth, then it becomes waste and next it becomes an object for everyday use. Just like that, the use, meaning and composition of the glass have changed several times, yet it is still part of the same glass flow.

5.4.5 ‘Life history’ of the Sagalassos glass flow

The core of the glass flow of Sagalassos seems to consist of colourless, mainly unrecycled vessel glass from Egypt Alexandria and Syro-Palestine. Through time, the stream of glass develops and even though the changes are sometimes small, they are there in and between every time period. For example the fluctuating amount of available green and blue glass. Although these colours could be obtained over the entire time period covered in this research (1-700 AD), they seem to have become more popular in P4. The larger amount of colourless glass in comparison with the amount of green and blue glass might be related to trade restrictions. However, it is known that Sagalassos had a strong economy and was connected to a broad trade network. It is therefore more likely that the amount of available glass of a specific colour was linked with the preferences of people. With what they considered good-looking and fashionable. The colours purple, cobalt blue and yellow-green are added to the glass flow in P4, which is a clear example of new input of material into the glass system of Sagalassos. Another input of new material can be determined with help from lead isotope ratios. These show a change through time, indicating the likely use of several raw materials for the same primary glass in different time periods.

Notable is also that for the 4th time period more samples of window glass are at hand. The use of glass for this function apparently became more popular. This could be connected with the introduction of Christianity into the city, because of which several churches with windows were built. P4 is further characterized by the considerable increase of glass with the provenance Egypt HIMT. A fourth of all the samples with an Egypt HIMT provenance is recycled, which demonstrates that at the same time new materials were added to the glass flow and that current and new materials were mixed. On the other hand, material with a known provenance also disappeared from the glass flow. In the sense that the primary provenance is no longer detectable because of too many changes in the composition of the glass. In this way, glass with the provenance west Mediterrenean disappears in P3 and P4. Some of the samples with this origin in P1 and P2 are recycled, which makes it likely that despite frequent recycling, components of this glass are still part of the glass flow. Even though they cannot be recognized as such anymore. Recycling and mixing thus cause changes and influence the visibility of glass types in the glass flow at certain points in time.

Through time the amount of glass from Sagalassos that is recycled is quite stable (around 30%). This means that there was a continuous mixing and movement of materials in the glass flow, which clearly shows the changing nature of glass while in circulation. It is therefore not surprising that all glass colours have indications for recycling. Yet, it is clear that some colours, like green and blue, were rather preferred to use for recycling than other colours. A possibility is that other, now unrecognizable, colours were also frequently used in recycling, but that green and blue glass still formed the largest part or turned out to be the dominant colours and were therefore defining the final colour. If so, the disappeared colours are again an example of material that is still present in the glass flow, yet through change no longer recognizable in its original state. Recycling also causes the lead isotope and chemical composition to become more homogeneous. How longer recycling continues in a flow of glass, how more homogeneous it will become. Therefore, unless regular inputs are added to a flow, less and less characteristics can be used to distinguish specific glass types, colours and provenances from the entire glass flow.

Despite that only the time period of 1-700 AD is described in this research, the above is a good example of part of the life history of the Sagalassos glass flow.

5.5 Further research

Although 87.6% of the samples has a known provenance and from 58% the recycling is clear, it will be better if the dataset could be analysed more completely. Therefore, further, more extensive research can be advised. To complement the provenance determinations, more precise threshold values and criteria, like Zr and Sr values, for the known provenance groups can be helpful. This is especially the case for the group with a west Mediterranean origin. Also, new chemical data from the glass samples needs to be obtained, primarily εNd values and Zr and Sr values are important as well. To expand the recycling analysis, mainly Sb values are needed, but also Pb, Co, Ni, Cu and Zn values will be useful. Lastly, it is advised to expand the lead isotope analysis through obtaining more lead isotope ratios and chemical lead values of the 243 samples. At the moment these values are only known for 28 samples. By collecting additional measurements and calculations a more representative overview of the whole dataset can be created. With all this additional information it should be possible to make more complete and reliable provenance, recycling, lead isotope and combined analyses of the Sagalassos glass and its flow.

6. Conclusion

This research concerns the combined analysis of chemical and lead isotopic data of Roman glass from the ancient city of Sagalassos (south-west Turkey). By combining the two analysing techniques, a new approach for interpreting data can be used. The aim of this research therefore is to test this new method of interpretation, similar to the method that was used to map the flow of metal from the Bronze Age (project FLAME), and to test in which manner and extent the method will be successful in looking at glass materials from one context. The main research question is therefore: Is the proposed method for interpretation, according to the approach in Pollard and Bray (2015), with elemental and isotopic data suitable for mapping 'the flow of glass' of glass assemblages from Sagalassos (south-west Turkey) dating from 1-675 AD? This question is supported by three other research questions.

1. How can the changing nature of the chemical and lead isotope composition of the glass assemblages from Sagalassos be interpreted? What are the striking changes and similarities between the 'fingerprints' of the glass assemblages from the subsequent time periods?
2. Is it possible and to what extent, to identify the timing and general origin of new inputs of glass into the system of the assemblages from Sagalassos?
3. Is it possible to interpret such changes in a social-geographical context?

The method of data analysis turned out to be a success. Although more detailed chemical and lead isotope data could have made the analyses completer, a clear overview of all the 243 samples has been created. The method is not exactly the same as the one described in Pollard and Bray (2015). However, it is very similar and only the necessary adjustments were made in order to use the method for glass analysis instead of metal. An advantage of the used method was the classification of data into groups, which made it easier to analyse the data into detail.

Considering research question one, a summary of the most important results of the analysis, in which the changes of the chemical and lead isotope composition through time are reflected, is the best answer to this question. Overall, the provenance of the 243 glass samples is 33.7% Egypt Alexandria, 32.5% Syro-Palestine, 18.5% Egypt HIMT, 12.4% Unknown and 2.9% west Mediterranean.

From 1 to 700 AD there is a continuous presence of the two largest provenance groups. The total amount of glass from Egypt Alexandria seems to decrease slightly over time, from 39% in P1 to 33% in P4. Yet, the amount of Syro-Palestine glass is more constant through time, around 30% in P1, P3 and P4, with the exception of 45% in P2. Glass with the provenance Egypt HIMT follows later in time, it was produced and available from the 4th century onwards (P3 and P4). Samples that originate in the west Mediterrenean are outnumbered and all date in the first two time periods (P1 and P2). Every provenance group contains samples of all the main colours. The largest amount of samples is colourless, a smaller amount is green and blue coloured and even less samples have a yellow-green colour. Colourless, blue and yellow-green glass have a homogeneous lead isotope composition and green glass is heterogeneous.

The overall recycling through time is quite stable, with about 30% recycled glass, 26% unrecycled glass and for 43% recycling is unclear. Recycling was done with glass from all available colours and provenance groups, but some were more preferred that others. The provenance group Egypt Alexandria and colourless glass were the least used for recycling and the provenances Syro-Palestine and west Mediterrenean and blue and green coloured glass were used most frequent for recycling. The lead isotope ratios of unrecycled glass are much wider in range than those of the recycled samples. Considering that recycling causes the lead isotope composition to become more homogeneous, this is no surprise. In general the differences in and between the lead isotope ratios are small. However, the different isotope ratios for P1 and P4 also indicate that over time they have slightly increased or decreased, depending on the kind of ratio, and that some change has occurred in their composition. Glass from Egypt Alexandria and Syro-Palestine has a homogeneous lead isotope composition, while the composition of samples with an Egypt HIMT provenance is heterogeneous.

The answer to the second research question is positive, yes it is possible to identify the timing and general origin of new inputs of glass into the Sagalassos glass flow. The extent in which this can be identified differs, sometimes it can be determined into detail. For the Sagalassos glass, the core of the glass flow and some other, smaller and faster changing elements of the flow could be identified. The provenance of new inputs was often easier to determine than the timing, but they could also be connected with each other. Glass from Egypt Alexandria is more recycled in P1 than in P4, which points out that there is more new input of this glass in P4 than in P1. There is also a large increase and new input of Egypt HIMT glass in P4. Nonetheless, it needs to be taken into account that the provenance and timing of additional glass to the flow can only be identified to a certain extent. When new glass is added to the flow it still has its characteristics that can determine its origin and the moment it became part of the flow. However, how longer glass (objects) is part of the flow, especially when recycling is involved, how more homogeneous its composition will become. Finally, the glass will lose all of its original characteristics. When this happens, it will no longer be possible to recognize its primary provenance, colour or timing of the addition to the glass flow.

Moving on, the answer to the third research question is also yes. Although it is not always possible to describe the changes in the glass flow into detail, they can frequently be placed in a social-geographical context. The presence of west Mediterrenean glass is such a change. The lack of this glass in P3 and P4 suggests that the import of it came to a halt, which can be explained by the stop of glass production in this area in the 4th century AD and possibly by the downfall of the west Roman Empire around this time. The types of glass that were available in Sagalassos are connected to the possibilities of the time. West Mediterrenean glass was most likely available in Sagalassos because the Romans ruled over a large area and long distance trade was therefore made easier. The large amount of glass from Egypt Alexandria and Syro-Palestine can be explained by the relatively closeness of these primary production centres, excellent trade connections and the continuous production of this glass from the 1st to 9th century AD. Moreover, statements about trade can thus be made. Besides that, changes in glass function can sometimes be brought into context with historical known events, like the increase of window glass after the introduction of Christianity in Sagalassos.

Taking all the results into account, the aims of this research have been fully reached and the answer to the main research question is yes. The proposed method for interpretation, according to the approach in Pollard and Bray (2015), is suitable for mapping ‘the flow of glass’ of glass samples from Sagalassos dating from 1-675 AD. A general view of the Sagalassos glass flow could be created with the available snapshots of information, but it will be harder to establish a very detailed overview of the flow. In this research, the flow of glass from a clear and limited time period and geographical area could be determined. Since the flow began and continued outside this time period, it needs to be realised that determining the entire Sagalassos glass flow through time will be more complicated than this research might suggests. Furthermore, the whole Bronze Age metal flow of Eurasia is taken into account in the project FLAME. It is probably also, partly, possible to determine such an extensive glass flow, yet it would certainly become more complex than the Sagalassos glass flow. Another difficulty in determining such an extensive glass flow might be that it is not known if the adjustments that were made in the method of Pollard and Bray (2015) to analyse glass instead of metal are suitable to use for large-scale research. It is therefore recommended to further test this method of interpretation for glass analysis in future research. When this is done, it is not only important to test this with more case studies, but also to enlarge the time period and geographical area of the case studies. Additionally, the proposed method in this research can be evaluated after using it for several case studies and possibly be developed and perfected. When this way of interpretation is consistently proofed to be reliable and a success it can be widely used for glass analysis.

7. Abstract

This research concerns the combined analysis of chemical and lead isotopic data of Roman natron glass samples from Sagalassos dating from 1-700 AD. It is based on a new way of interpreting data that also takes the effects of complex human actions on the material composition and the period of time in which an object moves from its source to archaeological deposition into account. Project FLAME has used this method for interpretation successful to map the flow of Bronze Age metal in Eurasia. The aims of this research are to test this new method of interpretation, to determine in which manner and extent it is successful in looking at glass materials from one context and if it can be used to characterize the flow of glass. This leads to the main research question 'Is the proposed method for interpretation, according to the approach in Pollard and Bray (2015), with elemental and isotopic data suitable for mapping 'the flow of glass' of glass assemblages from Sagalassos (south-west Turkey) dating from 1-675 AD?'.

Besides this main question, there are three supporting research questions. Answers to these questions were obtained through extensive data analysis. The multiple analyses are based on already known chemical and lead isotope data from 243 glass samples, no new samples were obtained especially for this research. The data has been used to make new interpretations by organizing, classifying and interpreting it in a different way. From all the data, 2 databases in Excel were made. These were used to make detailed analyses, tables and diagrams in Excel and Word, from which interpretations and conclusions could be made.

The data is mostly classified into the groups time period, glass colour, provenance and recycling. This division makes it possible to indicate changes, similarities and differences in and between the chemical and lead isotope data. Important provenance observations are the continuous presence of glass from the provenances Egypt Alexandria and Syro-Palestine, the disappearance of west Mediterrenean glass in later time periods and the large increase of glass from Egypt HIMT in the last time period. Every provenance group and time period contains samples of all the main colours and both recycled and unrecycled samples. The provenance group Egypt Alexandria and colourless glass were the least used for recycling and the provenances Syro-Palestine and west Mediterrenean and blue and green coloured glass were used most frequent for

recycling. Together, all these pieces of information have been used to determine the flow of glass and to describe its life history.

The answers to the research questions are positive. The short summary in the above standing paragraph indicates some changes in the glass flow. It is further possible to identify, to a certain extent, the timing and general origin of new inputs into the Sagalassos glass flow and to interpret some of these changes in a social-geographical context. For the Sagalassos glass, the core of the glass flow and some other, smaller and faster changing elements of the flow could be identified. Overall, the answer to the main research question is yes, the proposed method for interpretation, according to the approach in Pollard and Bray (2015), is suitable for mapping ‘the flow of glass’ of glass samples from Sagalassos dating from 1-675 AD. Further research to test this method of interpretation more often and in a broader context is recommended. When it is consistently proofed to be reliable and a success, it can be widely used for glass analysis.

Websites

http://flame.arch.ox.ac.uk/index.html#home, accessed on July and August 2018.

http://oxalid.arch.ox.ac.uk/The%20Database/TheDatabase.htm, accessed on June and July 2018.

http://tursaga.com/nl/album/fotos, accessed on 4th of September 2018.

https://whc.unesco.org/en/tentativelists/5409/, accessed on 8th and 9th of August 2018.

https://www.arts.kuleuven.be/sagalassos/history, accessed on 8th and 9th of August 2018.

Bibliography

Artioli, G., 2010. *Scientific Methods and Cultural Heritage: An introduction to the application of materials science to archaeometry and conservation science*. Oxford: Oxford University Press.

Baron, S., C.G. Tamas and C. Le Carlier, 2014. How mineralogy and geochemistry can improve the significance of Pb isotopes in metal provenance studies. *Archaeometry* 56(4), 665-680.

Bode, M., A. Hauptmann and K. Mezger, 2009. Tracing Roman lead sources using lead isotope analyses in conjunction with archaeological and epigraphic evidence - a case study from Augustan/Tiberian Germania. *Archaeological and Anthropological Sciences* 1, 177-194.

Bray, P.J. and A.M. Pollard, 2012. A new interpretative approach to the chemistry of copper-alloy objects: source, recycling and technology. *Antiquity* 86, 853-867.

Bray, P., A. Cuénod, C. Gosden, P. Hommel, R. Liu and A.M. Pollard, 2015. Form and flow: the 'karmic cycle' of copper. *Journal of Archaeological Science* 56, 202-209.

Brems, D., P. Degryse, M. Ganio and S. Boyen, 2012a. The production of Roman glass with western Mediterranean sand raw materials: preliminary results. *Glass Technology: European Journal of Glass Science and Technology* Part A, 1-25.

Brems, D., P. Degryse, F. Hasendoncks, D. Gimeno, A. Silvestri, E. Vassilieva, S. Luypaers and J. Honings, 2012b. Western Mediterranean sand deposits as a raw material for Roman glass production. *Journal of Archaeological Science* 39, 2897-2907.

Darnay, A. and W.E. Franklin, 1972. *Salvage Markets for Materials in Solid Wastes*. Washington (DC): U.S. Environmental Protection Agency.

Degryse, P. (ed), 2014. *Glass making in the Greco-Roman world. Results of the ARCHGLASS project*. Leuven: Leuven University Press.

Degryse, P., 2016. Chemical signature and scale of production of primary glass factories around the Mediterranean in the first millennium AD, *AIHV Annales du 20^{e} Congrès, 7-11 September 2015*. Fribourg: Romont/ Suisse, 1-6.

Degryse, P. and A.J. Shortland, 2009. Trace elements in provenancing raw materials for Roman glass production. *Geologica Belgica* 12(3-4), 135-143.

Degryse, P. and D. Braekmans, 2014. Elemental and isotopic analysis of ancient ceramics and glass, in H.D. Holland and K.K. Turekian (eds), *Treatise on Geochemistry, Second edition, Volume 14*. Oxford: Elsevier, 191-207.

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.

Degryse, P., J. Schneider, J. Poblome, M. Waelkens, U. Haack and P. Muchez, 2005. A geochemical study of Roman to early Byzantine glass from Sagalassos, South-west Turkey. *Journal of Archaeological Science* 32, 287-299.

Degryse, P., J. Schneider, U. Haack, V. Lauwers, J. Poblome, M. Waelkens and Ph. Muchez, 2006. Evidence for glass 'recycling' using Pb and Sr isotopic ratios and Sr-mixing lines: the case of early Byzantine Sagalassos. *Journal of Archaeological Science* 33, 494-501.

Degryse, P., J. Schneider, V. Lauwers, J. Henderson, B. Van Daele, M. Martens, H. Huisman, D. De Muynck and Ph. Muchez, 2009. Neodymium and strontium isotopes in the provenance determination of primary natron glass production, in P. Degryse, J. Henderson and G. Hodgins (eds), *Studies in Archaeological Sciences. Isotopes in Vitreous Materials*. Leuven: Leuven University Press, 51-70.

Degryse, P., R.B. Scott and D. Brems, 2014. The archaeometry of ancient glassmaking: reconstructing ancient technology and trade of raw materials. *Antiquité* 2, 31-46.

Freestone, I.C., 2003. Primary glass sources in the mid first millennium AD, *AIHV Annales du 15^{e} Congrès, 2001*. New York: Corning, 111-115.

Freestone, I.C., 2005. The Provenance of Ancient Glass through Compositional Analysis. *Materials Research Society Symposia Proceedings* 852, 008.1.1-008.1.14.

Freestone, I.C., 2006. Glass production in Late Antiquity and the Early Islamic period: a geochemical perspective. *Glass Production*, 1-28.

Freestone, I.C. and Y. Gorin-Rosen, 1999. The great glass slab at Bet She'arim, Israel: an early Islamic glassmaking experiment. *Journal of Glass Studies* 41, 105-115.

Freestone, I.C., R.E. Jackson-Tal and O. Tal, 2008. Raw Glass and the Production of Glass Vessels at Late Byzantine Apollonia-Arsuf, Israel. *Journal of Glass Studies* 50, 67-80.

Freestone, I.C., S. Wolf and M. Thirlwall, 2003. The production of HIMT glass: Elemental and isotopic evidence, *Annales du 16^{e} Congres de l'Association Internationale pour l'Histoire du Verre*, *2003*. Londen, 153-157.

Freestone, I.C., Y. Gorin-Rosen and M.J. Hughes, 2000. Primary glass from Israel and the production of glass in late Antiquity and the early Islamic period, in *La Route du verre. Ateliers primaires et secondaires du second millénaire av. J.-C. au Moyen Âge. Colloque organisé en 1989 par l'Association française pour l'Archéologie du Verre (AFAV) Lyon: Maison de l'Orient et de la Méditerranée Jean Pouilloux, 2000, 65-83*.

Freestone, I.C., Y. Gorin-Rosen, S. Wolf and M. Thirlwall, 2009. Isotopic composition of glass from the Levant and the south-eastern Mediterranean Region, in P. Degryse, J. Henderson and G. Hodgins (eds), *Isotopes in Vitreous Materials*. Leuven: Leuven University Press, 29-50.

Gale, N.H., Z.A. Stos-Gale, G. Maliotis and N. Annetts, 1997. Lead isotope data from the isotrace laboratory, Oxford: Archaeometry data base 4, ores from Cyprus. *Archaeometry* 39(1), 237-246.

Ganio, M., S. Boyen, T. Fenn, R. Scott, S. Vanhoutte, D. Gimeno and P. Degryse, 2012. Roman glass across the Empire: an elemental and isotopic characterization. *Journal of Analytical Atomic Spectrometry* 27, 743-753.

Henderson, J., 1985. The raw materials of early glass production. *Oxford Journal of Archaeology* 4(3), 267-291.
Henderson, J., 2002. Tradition and experiment in first millennium A.D. glass production. The emergence of Early Islamic glass technology in Late Antiquity. *Accounts of Chemical Research* 35, 594-602.

Huelga-Suarez, G., M. Moldovan, M. Suarez Fernandez, M. Angel De Blas Cortina, F. Vanhaecke and J.I. Garcia Alonso, 2012. Lead isotopic analysis of copper ores from the Sierra el Aramo (Asturias, Spain). *Archaeometry* 54(4), 685-697.

Klein, S., G.P. Brey, S. Durali-Müller and Y. Lahaye, 2010. Characterisation of the raw metal sources used for the production of copper and copper-based objects with copper isotopes. *Archaeological and Anthropological Sciences* 2, 45-56.

Klein, S., Y. Lahaye and G.P. Brey, 2004. The early Roman Imperial Aes coinage II: Tracing the copper sources by analysis of lead and copper isotopes – copper coins of Augustus and Tiberius. *Archaeometry* 46(3), 469-480.

Lauwers, V., P. Degryse and M. Waelkens, 2007a. Evidence for Anatolian glassworking in Antiquity: the case of Sagalassos (Southwestern Turkey). *Journal of Glass Studies* 49, 39-46.

Lauwers, V., P. Degryse and M. Waelkens, 2007b. A ceramic tool for the glass blower. *Oxford Journal of Archaeology* 26(2), 193-200.

Lauwers, V., P. Degryse and M. Waelkens, 2009. The glass of the church and shop complex of the upper agora of Sagalassos (Turkey), in K. Janssens, P. Degryse, P. Cosyns, J. Caen and L. Van 't Dack (eds), *AIHV Annales du 17^e Congrès, 2006*. Antwerp: Aspeditions, 7-13.

Müller, R., G.P. Brey, H.M. Seitz and S. Klein, 2015. Lead isotope analyses on Late Republican sling bullets. *Archaeological and Anthropological Sciences* 7, 473-485.

Nenna, M.D., M. Picon and M. Vichy, 2000. Ateliers primaires et secondaires en Égypte à l'époque gréco-romaine, in *La Route du verre. Ateliers primaires et secondaires du second millénaire av. J.-C. au Moyen Âge. Colloque organisé en 1989 par l'Association française pour l'Archéologie du Verre (AFAV) Lyon: Maison de l'Orient et de la Méditerranée Jean Pouilloux, 2000*, 97-112.

Ostende, F., Van den, 2015. *Geochemical study of glass batches and recycling at Roman-Byzantine Sagalassos*. Leuven (unpublished master thesis University of Leuven and Gent).

Pollard, A.M. and P.J. Bray, 2015. A new method for combining lead isotope and lead abundance data to characterise archaeological copper alloys. *Archaeometry* 57(6), 996-1008.

Pollard, A.M., P.J. Bray and C. Gosden, 2014. Is there something missing in scientific provenance studies of prehistoric artefacts? *Antiquity* 88, 625-631.

Rohl, B.M., 1996. Lead isotope data from the Isotrace Laboratory, Oxford: Archaeometry data base 2, galena from Britain and Ireland. *Archaeometry* 38(1), 165-180.

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.

Stos-Gale, Z.A., N.H. Gale and N. Annetts, 1996. Lead isotope data from the isotrace laboratory, Oxford: Archaeometry data base 3, ores from the Aegean, part 1. *Archaeometry* 38(2), 381-390.

Stos-Gale, Z.A., N.H. Gale, N. Annetts, T. Todorov, P. Lilov, A. Raduncheva and I. Panayotov, 1998. Lead isotope data from the isotrace laboratory, Oxford: Archaeometry data base 5, ores from Bulgaria. *Archaeometry* 40(1), 217-226.

Trincherini, P.R., C. Domergue, I. Manteca, A. Nesta and P. Quarati, 2010. The identification of lead ingots from the Roman mines of Cartagena (Murcia, Spain): the role of lead isotope analysis. *Journal of Roman Archaeology* 22(1), 123-145.

Waelkens, M., 2002. Romanization in the East. A case study: Sagalassos and Pisidia (SW Turkey). *Istanbuler Mitteilungen* 52, 311-368.

Waelkens, M. and the Sagalassos Team, 2011. *Sagalassos Visitor's Companion*. Published as part of the project "Development and Promotion of Cultural and Natural Resources of Ağlasun for Sustainable Tourism Use" (http://www.tursaga.com/en/publications).

Wilson, L. and A.M. Pollard, 2001. The provenance hypothesis, in D.R. Brothwell and A.M. Pollard (eds), *Handbook of Archaeological Sciences*. Chichester: John Wiley and Sons UK, 508-517.

Wolf, S., S. Stos, R. Mason and M.S. Tite, 2003. Lead isotope analyses of Islamic pottery glazes from Fustat, Egypt. *Archaeometry* 45(3), 405-420.

Yener, K.A., E.V. Sayre, E.C. Joel, H. Özbal, I.L. Barnes and R.H. Brill, 1991. Stable lead isotope studies of central Taurus ore sources and related artifacts from Eastern Mediterranean Chalcolithic and Bronze Age sites. *Journal of Archaeological Science* 18, 541-577.

Zalduegui, J.F.S., S.G. de Madinabeitia and J.I.G. Ibarguchi, 2004. A lead isotope database: The Los Pedroches – Alcudia area (Spain); implications for archaeometallurgical connections across southwestern and southeastern Iberia. *Archaeometry* 46(4), 625-634.

List of figures, tables and appendices

Figures

Tables

Appendices

Appendices

Appendix 1: Tables with data for recycling analysis

Table 1.1: Overview of recycling for period 1.

	No	Yes	?	**Total**
Colourless	6	2	4	**12**
Green (pale)	2	2	4	**8**
Aqua/blue	0	5	6	**11**
Other	1	0	1	**2**
Total	**9**	**9**	**15**	**33**
% of P1	**27,3**	**27,3**	**45,4**	**100%**

Table 1.2: Overview of recycling for period 2.

	No	Yes	?	**Total**
Colourless	7	2	1	**10**
Green (pale)	0	2	0	**2**
Aqua/blue	1	2	1	**4**
Other	1	1	2	**4**
Total	**9**	**7**	**4**	**20**
% of P2	**45**	**35**	**20**	**100%**

Table 1.3: Overview of recycling for period 3.

	No	Yes	?	**Total**
Colourless	10	9	12	**31**
Green (pale)	2	2	4	**8**
Aqua/blue	0	0	1	**1**
Other	0	2	1	**3**
Total	**12**	**13**	**18**	**43**
% of P3	**27,9**	**30,2**	**41,9**	**100%**

Table 1.4: Overview of recycling for period 4.

	No	Yes	?	**Total**
Colourless	21	9	11	**41**
Green (pale)	8	14	15	**37**
Aqua/blue	2	6	12	**20**
Cobalt blue	0	3	6	**9**

Yellow-green	2	4	7	**13**
Purple	0	0	3	**3**
Other	0	2	5	**7**
Total	**33**	**38**	**59**	**130**
% of P4	**25,4**	**29,2**	**45,4**	**100%**

Table 1.5: Overview of recycling for period X.

	No	Yes	?	**Total**
Colourless	3	2	2	**7**
Green (pale)	1	3	3	**7**
Aqua/blue	0	2	1	**3**
Other	0	0	0	**0**
Total	**4**	**7**	**6**	**17**
% of Px	**23,5**	**41,2**	**35,3**	**100%**

Table 1.6: Overview of recycling for colourless glass, in amount of samples and percentages.

Period	No	No%	Yes	Yes%	?	?%	Amount of samples
P1	6	50	2	16,7	4	33,3	12
P2	7	70	2	20	1	10	10
P3	10	32,3	9	29	12	38,7	31
P4	21	51,2	9	22	11	26,8	41
Px	3	42,8	2	28,6	2	28,6	7
Total	**47**	**46,5%**	**24**	**23,8%**	**30**	**29,7%**	**101**

Table 1.7: Overview of recycling for green glass, in amount of samples and percentages.

Period	No	No%	Yes	Yes%	?	?%	Amount of samples
P1	2	25	2	25	4	50	8
P2	0	0	2	100	0	0	2
P3	2	25	2	25	4	50	8
P4	8	21,6	14	37,8	15	40,5	37
Px	1	14,3	3	42,9	3	42,9	7
Total	**13**	**21%**	**23**	**37,1%**	**26**	**41,9%**	**62**

Table 1.8: Overview of recycling for aqua/blue glass, in amount of samples and percentages.

Period	No	No%	Yes	Yes%	?	?%	Amount of samples
P1	0	0	5	45,5	6	54,5	11
P2	1	25	2	50	1	25	4
P3	0	0	0	0	1	100	1
P4	2	10	6	30	12	60	20
Px	0	0	2	75	1	25	3
Total	**3**	**7,7%**	**15**	**38,5%**	**21**	**53,8%**	**39**

Table 1.9: Overview of recycling for 'other' coloured glass, in amount of samples and percentages.

Period	No	No%	Yes	Yes%	?	?%	Amount of samples
P1	1	50	0	0	1	50	2
P2	1	25	1	25	2	50	4
P3	0	0	2	75	1	25	3
P4	0	0	2	28,6	5	71,4	7
Px	0	0	0	0	0	0	0
Total	**2**	**12,5%**	**5**	**31,3%**	**9**	**56,2%**	**16**

Table 1.10: Overview of recycling for the provenance Syro-Palestine, in amount of samples and percentages.

Period	No	No%	yes	Yes%	?	?%	Amount of samples
P1	1	11,1	1	11,1	7	77,8	9
P2	5	55,6	3	33,3	1	11,1	9
P3	2	14,3	7	50	5	35,7	14
P4	5	12,5	16	40	19	47,5	40
Px	2	28,6	4	57,1	1	14,3	7
Total	**15**	**19%**	**31**	**39,2%**	**33**	**41,8%**	**79**

Table 1.11: Overview of recycling for the provenance Egypt HIMT, in amount of samples and percentages.

Period	No	No%	yes	Yes%	?	?%	Amount of samples
P1	0	0	0	0	2	100	2
P2	0	0	1	100	0	0	1
P3	0	0	1	25	2	75	3

P4	8	22,9	9	25,7	18	51,4	35
Px	0	0	1	25	3	75	4
Total	**8**	**17,8%**	**12**	**26,7%**	**25**	**55,5%**	**45**

Table 1.12: Overview of recycling for the provenance Egypt Alexandria, in amount of samples and percentages.

Period	No	No%	yes	Yes%	?	?%	Amount of samples
P1	7	53,8	5	38,5	1	7,7	13
P2	4	57,1	2	28,6	1	14,3	7
P3	8	50	2	12,5	6	37,5	16
P4	19	44,2	7	16,3	17	39,5	43
Px	1	25	0	0	2	75	3
Total	**39**	**47,6%**	**16**	**19,5%**	**27**	**32,9%**	**82**

Table 1.13: Overview of recycling for the provenance west Mediterranean, in amount of samples and percentages.

Period	No	No%	yes	Yes%	?	?%	Amount of samples
P1	0	0	2	40	3	60	5
P2	0	0	1	50	1	50	2
P3	0	0	0	0	0	0	0
P4	0	0	0	0	0	0	0
Px	0	0	0	0	0	0	0
Total	**0**	**0%**	**3**	**42,9%**	**4**	**57,1%**	**7**

Table 1.14: Overview of recycling for the provenance Unknown, in amount of samples and percentages.

Period	No	No%	yes	Yes%	?	?%	Amount of samples
P1	1	25	1	25	2	50	4
P2	0	0	0	0	1	100	1
P3	2	20	3	30	5	50	10
P4	1	8,3	6	50	5	41,7	12
Px	1	25	2	75	0	0	3
Total	**5**	**16,7%**	**12**	**40%**	**13**	**43,3%**	**30**

Appendix 2: Overview of average lead isotope ratios of areas in the Mediterranean and Europe

Area	**Objects/context**	**Time**	**^{206}Pb/^{204}Pb**	**^{207}Pb/ ^{204}Pb**	**^{208}Pb/^{204}Pb**	**^{207}Pb/^{206}Pb**	**^{208}Pb/^{206}Pb**	**Literature**
Turkey - Sagalassos (EA)	4 recycled glass samples with provenance Egypt Alexandria	1-700 AD	18,543 min: 18,472 max: 18,618	15,667 min: 15,658 max: 15,685	38,661 min: 38,581 max: 38,772	0,845 min: 0,842 max: 0,848	2,085 min: 2,080 max: 2,089	Own data.
Turkey - Sagalassos (SP)	2 recycled glass samples with provenance Syro-Palestine	1-700 AD	18,614 min: 18,586 max: 18,641	15,680 min: 15,677 max: 15,682	38,756 min: 38,738 max: 38,773	0,842 min: 0,841 max: 0,844	2,082 min: 2,080 Max: 2,084	Own data.
Aegean/ Greece	unknown	-	-	-	-	Between 0,826-0,839	Between 2,05-2,09	Klein *et al.* 2004: (figure 1, p. 471). Klein *et al.* 2010.
Greece	802 samples of Pb/Cu/Fe ore/slag/litharge	-	18,781 Min: 17,833 Max: 19,630	-	-	0,835 Min: 0,805 Max: 0,875	2,070 Min: 1,952 Max: 2,127	http://oxalid.arch.ox.ac.uk/Greece/Greece.html Stos-Gale *et al.* 1996.
Cyprus	unknown	-	-	-	-	Between 0,821-0,847	Between 2,041-2,084	Klein *et al.* 2004: (figure 1, p. 471). Klein *et al.* 2010.
Cyprus	279 Cu/Fe/S/Ni/As/Pb ore samples from	-	18,613 Min: 18,404 Max: 19, 016	-	-	0,838 Min: 0,821 Max: 0,846	2,072 Min: 2,043 Max: 2,083	http://oxalid.arch.ox.ac.uk/Cyprus/Cyprus.html Gale *et al.* 1997.

	different mines and dumps							
Spain – SE	unknown	-	-	-	-	Between 0,831-0,840	Between 2,065-2,09	Klein *et al.* 2004: (figure 1, p. 471).
Spain – SW	unknown	-	-	-	-	Between 0,858-0,862	Between 2,096-2,112	Klein *et al.* 2004: (figure 1, p. 471).
Spain – SW and S (e.g. provinces Sevilla, Huelva, Cadiz and Almeria)	163 samples of Pb/Cu/Fe/Si ore/slag/litharge	-	18,418 < 18,350 mainly from province of Sevilla, Huelva and Cadiz 18,350-18,555 mainly from province of Huelva >18,555 mainly from province of Almeria Min: 18,079 Max: 19,077	-	-	0,850 <0,8458 mainly province of Almeria >0,8458 mainly province of Sevilla, Huelva and Cadiz Min: 0,8233 Max: 0,8628	2,092 <2,082 mainly province of Almeria >2,082 mainly province of Sevilla, Huelva and Cadiz Min: 2,049 Max: 2,115	http://oxalid.arch.ox.ac.uk/Spain/Spain.html
Spain – Portman	2 ores with provenance Cartagena	-	18,716 18,718	15,676 15,676	38,988 38,985	0,838 0,837	2,083 2,083	Müller *et al.* 2015, 475, 476.

Spain – S'Argentera	1 ore with provenance Ibiza	-	18,670	15,681	38,923	0,840	2,0845	Müller *et al.* 2015, 475, 476.
Spain north-west (Asturias)	20 ore samples, azurite/malachite from a prehistoric mine (partly from waste mineral heap)	-	19,249 Min: 18,821 Max: 20,348	15,779 Min: 15,713 Max: 16,127	38,883 Min: 38,679 Max: 40,068	0,820 Min: 0,777 Max: 0,835	2,022 Min: 1,905 Max: 2,071	Huelga-Suarez *et al.* 2012, 693.
South-Spain (Los Pedroches - Alcudia Valley)	86 ore samples, galena	-	18,097 Min: 17,735 Max: 18,269	-	-	0,863 Min: 0,856 Max: 0,877	2,112 Min: 2,101 Max: 2,127	Zalduegui *et al.* 2004.
Italy – Liguria	15 Cu/Pb/Fe ore samples	-	18,389 Min: 17,977 Max: 20,531	-	-	0,847 Min: 0,765 Max: 0,862	2,061 Min: 1,881 Max: 2,102	http://oxalid.arch.ox.ac.uk/Italy/Italy.html
Italy – Tuscany	49 Pb/Cu ore samples	-	18,709 Min: 17,994 Max: 18,815	-	-	0,839 (46 samples <0,838) Min: 0,836 Max: 0,861	2,083 Min: 2,078 Max: 2,091	http://oxalid.arch.ox.ac.uk/Italy/Italy.html
Italy – Tuscany	unknown	-	-	-	-	Between 0,836-0,862	Between 2,072-2,09	Klein *et al.* 2004: (figure 1, p. 471).
Italy – Sardinia	unknown	-	-	-	-	Between 0,848-0,875	Between 2,088-2,129	Klein *et al.* 2004: (figure 1, p. 471).

Italy - Sardinia	250 Pb/Cu/Fe/Ag/ ore samples	-	18,291 Min: 17,848 Max: 19,531	-	-	0,856 <0,838 only Castello Di Bonvei, (SS) Min: 0,832 Max: 0,864	2,101 <2,078 mostly Castello Di Bonvei, (SS) Min: 2,063 Max: 2,128	http://oxalid.arch.ox.ac.uk/Italy/Italy.html
Germany	90 lead artefacts/debris and 5 ingots (military context)	Augustan /Tiberian	18,320 Min: 18,147 Max: 18,724	15,614 Min: 15,580 Max: 15,697	38,304 Min: 38,050 Max: 39,120	0,8523 Min: 0,8365 Max: 0,8594	2,091 Min: 2,075 Max: 2,101	Bode, Hauptmann and Mezger 2009.
Germany - BriD-Hoppecke quarry	14 samples of galena	Augustan /Tiberian	18,355 Min: 18,335 Max: 18,425	15,623 Min: 15,604 Max: 15,712	38,335 Min: 38,273 Max: 38,585	0,8511 Min: 0,8504 Max:0,8525	2,088 Min: 2,087 Max: 2,094	Bode, Hauptmann and Mezger 2009.
Germany - BriD-Kanzlei mine	7 samples of galena	Augustan /Tiberian	18,395 Min: 18,362 Max: 18,411	15,612 Min: 15,585 Max: 15,622	38,365 Min: 38,330 Max: 38,392	0,8487 Min: 0,8467 Max: 0,8506	2,085 Min: 2,084 Max: 2,087	Bode, Hauptmann and Mezger 2009.
Germany - MB- “Kallmuther Berg” (Kallmuth)	5 samples of galena	Augustan /Tiberian	18,330 Min: 18,303 Max: 18,372	15,612 Min: 15,599 Max: 15,628	38,300 Min: 38,246 Max: 38,376	0,8513 Min: 0,8505 Max: 0,8527	2,090 Min: 2,086 Max: 2,092	Bode, Hauptmann and Mezger 2009.

Germany - ASD-Hastenrath quarry (Stolberg)	11 samples of galena	Augustan /Tiberian	18,395 Min: 18,385 Max: 18,406	15,625 Min: 15,614 Max: 15,640	38,400 Min: 38,367 Max: 38,440	0,8494 Min: 0,8491 Max: 0,8497	2,088 Min: 2,087 Max: 2,089	Bode, Hauptmann and Mezger 2009.
Germany - BenD-Lüderich mine (Rösrath)	3 samples of galena	Augustan /Tiberian	18,168 Min: 18,148 Max: 18,180	15,613 Min: 15,595 Max: 15,630	38,132 Min: 38,079 Max: 38,189	0,8593 Min: 0,8590 Max: 0,8597	2,099 Min: 2,098 Max: 2,101	Bode, Hauptmann and Mezger 2009.
Turkey	51 Pb/Fe/Cu/Ag/Zn/Au ore samples	-	18,762 >18,961 mainly from region Elazig Min: 17,847 Max: 19,323	-	-	0,837 <0,826 only region Elazig 0,834-0,836 mainly region Cannakale Min: 0,817 Max: 0,875	2,074 <2,061 mainly region Elazig Min: 2,044 Max: 2,126	http://oxalid.arch.ox.ac.uk/Turkey/Turkey.html
Turkey – Taurus 1A	16 ore/slag samples	-	-	-	-	0,826	2,057	Yener *et al.* 1991, 560, 561.
Turkey – Taurus 1B	8 ore/slag samples	-	-	-	-	0,835	2,073	Yener *et al.* 1991, 560, 561.
Turkey – Taurus 2A	12 ore/slag samples	-	-	-	-	0,841	2,081	Yener *et al.* 1991, 560, 561.
Turkey – Taurus 2B	7 ore/slag samples	-	-	-	-	0,831	2,062	Yener *et al.* 1991, 560, 561.

Bulgaria	136 Pb/Cu/Fe ore samples	-	18,590 <18,437 mainly regions Lesovo and North-West >18,757 region South Min: 18,120 Max: 19,048	-	-	0,842 <0,837 mainly regions South and Burgas district >0,846 mainly regions North-west and Lesovo Min: 0,822 Max: 0,860	2,076 <2,067 mainly Burgas district >2,082 mainly regions North-west and Lesovo Min: 2,037 Max: 2,102	http://oxalid.arch.ox.ac.uk/Bulgaria/Bulgaria.html Stos-Gale *et al.* 1998.
British Isles	420 samples of Pb/Cu/Fe/Au/Zn ores	-	18,373 <18,268 mainly from Scotland and Wales >18,331 mainly from England Min: 17,253 Max: 21,162	-	-	0,851 0,835-0,851 mainly England >0,859 mainly from Wales Min: 0,746 Max: 0,914	2,088 2,065-2,091 mainly from England >2,101 mainly from Wales Min: 1,847 Max: 2,143	http://oxalid.arch.ox.ac.uk/British/British.html Rohl 1996.

Israel (Beersheva, Abu Matar)	39 Cu/Si/Fe ore samples	Chalcolithic	18,208 Min: 18,056 Max: 18,571	15,670 Min: 15,633 Max: 15,765	38,378 Min: 38,191 Max: 38,742	0,861 Min: 0,844 Max: 0,868	2,108 Min: 2,086 Max: 2,125	http://oxalid.arch.ox.ac.uk/The%20Database/TheDatabase.htm
France (Saintes-Maries-de-la-Mer)	4 lead ingots	Roman	18,394 Min:18,379 Max: 18,404	15,628 Min: 15,626 Max: 15,632	38,375 Min: 38,348 Max: 38,399	0,849 Min: 0,849 Max: 0,850	2,086 Min: 2,086 Max: 2,087	Baron *et al.* 2014, 676.
France - Cévennes (L'Argentière)	1 sample of galena	Augustan /Tiberian	18,319	15,650	38,486	0,8543	2,101	Bode, Hauptmann and Mezger 2009.
Egypt	Around 21 Pb ores	-	Between 17,250-20,750 Most: 18,500-19,600	-	-	Between 0,758-0,898 Most: 0,800-0,840	Between 1,976-2,140 Most: 2,000-2,070	Wolf *et al.* 2003, 412.

Appendix 3: Databases (digital)

The two databases that were made for this research are digital attachments in separate Excel documents. They contain all the chemical and lead isotope data that has been used in this research.