

UNIVERSITY OF NOTTINGHAM

Department of Archaeology

'Analysis of Hellenistic Glass from Satricum'

by

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I certify that:

- a)** The following dissertation is my own original work.
- b)** The source of all non-original material is clearly indicated.
- c)** All material presented by me for other modules is clearly indicated.
- d)** All assistance received has been acknowledged.

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Abstract

This dissertation is presented for an MSc (by Research) in Archaeological Materials. It covers a variety of topics relating to the ultimate goal: provenancing the samples of eleven glass artifacts found in a votive deposit at Satricum, Italy. This paper introduces the reader to the world of glass as a material, both from a cultural and scientific view. The history of the site of Satricum and the surrounding areas is explored in order to provide a background on the possible origins of the artifacts found there. A history of glass from its invention is also covered to explain the importance of glass artifacts and where they may have been made during the relevant time period. Eleven samples from glass fragments found at Satricum in Italy were analyzed. Dating from the third to second centuries BCE, the samples were all found in a votive deposit at the temple site during the excavations by the Satricum Project, which are currently run by the University of Amsterdam. Using the chemical analysis of the samples, by electron microprobe analysis run by Dr. Andy Tindle at the Open University, along with historical references and other evidence, probable provenances of the artifacts are suggested. Since there is a rather significant lack of information and evidence regarding the provenances of ancient glass, possible hypotheses instead of definite conclusions are discussed.

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Introduction

The aim of this dissertation is to determine the provenance of eleven glass artifacts found in a votive deposit at Satricum, Italy. Part One of this paper provides the reader with a background on the history of Italy and the relevant areas, as well as establishing an understanding of the ancient trade network in the Mediterranean. Part Two deals with ancient glass, specifically the history of its evolution, the difficulties in studying the material, and the science of glass as a material. In Part Three the samples from Satricum are analyzed and the results and conclusions are discussed. Ultimately the goal is trying to prove the provenance, or suggest possible origins, of the samples.

This dissertation is meant to be an introduction to the world of ancient glass; as this is such a niche area of study it is assumed that the reader may not be completely familiar with the topic. A range of subjects is discussed in length in order to give the reader a basic, but hopefully rather full, understanding of the topic and the issues surrounding it so the arguments and conclusions will make sense. Using the chemical analysis of the samples, historical references, and other evidence the author has attempted to provide a provenance of the artifacts. Unfortunately, given the lack of substantial data and the limited information on production sites during the relevant time period, only a vague guess can be suggested for the objects' provenances.

This is not a groundbreaking study on the topic of ancient glass, nor a final, definitive report on provenancing. Rather, this is a case study on one specific set of

glass fragments found together in a votive deposit. The samples provided to the author were already mounted in the resin block; removing artifacts from Italy, even to study, is quite difficult. No further information regarding their relevance to the site or photos of the samples was given beside the most basic description of color and, in some cases, possible vessel shape. To truly pinpoint a location of provenance would require isotopic analysis rather than analyzing the major elemental compositions, which was unavailable and too costly for this study. Furthermore, the lack of literary documentation before the Medieval Period in Europe and absence of glassmaking kilns for a seven hundred year span mean there is not much to start with when attempting to provenance artifacts. Glass production has lots of chances for variables. Subsequently, only suggestions for locations of provenance can be given for these samples, not a definitive answer. When it comes to provenancing ancient Mediterranean glass objects, there are more difficulties than certainties. These difficulties and variables will be described over the course of this paper and compiled in the Conclusions section.

**PART ONE - Historical
Background of Satricum and the
Mediterranean World until the
Roman Era**

1. History of Italy

Background

Beginning with the founding of Rome in the eighth century BCE, the Roman Era was one of the largest and longest ruling empires in history. Stretching from Britain and Spain to the Middle East and incorporating parts of Africa, the Roman Empire was a melting pot of ideas, cultures, mores, art, ideologies, and religions. Rome, lying roughly in the center of the territory, borrowed many of these foreign ideas, but also cultivated their own. For the most part, however, the Roman Empire was based on Greek influences. Even regardless of the direct trade from the Greeks in the east, a strong influence would have come from the Etruscans to the north. The Etruscans, in turn, were strongly influenced by the Greeks. This “trickle down” effect resulted in a Greek-based culture in Italy that would eventually become Roman.

The Etruscans

And so we come to the Etruscans, without whom it would be impossible to picture the history of the Italy of antiquity either in its origins or subsequently. (Pallottino 1991, 51)

The area of Etruria lay between the Tyrrhenian Sea and the western edge of the River Tiber and between the Arno River to the north and the Tiber to the south. It includes most of modern Tuscany and parts of Umbria and Latium. Archaeological evidence has proved that the first Etruscan inscriptions were created in the eighth century BCE, however they were most likely around before this time.

The Etruscans were highly influenced by the Greeks. An extensive sea trade route was established by the Phoenicians in the Mediterranean by the beginning of

the first millennium BCE. Around the ninth century BCE the Greeks began to colonize Sicily and Magna Graecia. With them came their cultures and traditions, “which had existed at an advanced level in the eastern Mediterranean for centuries; their written traditions are of invaluable assistance to us in illuminating the history of the peoples of Italy” (Bloch 1960, 28). Spreading northwards from Magna Graecia, many of them became ensconced in Etruria.

It seems that the first permanent interactions between the Etruscans and the Greeks occurred between 775 BCE and 750 BCE when the Greeks founded their first colony in Italy. These Greeks came from Euboea and settled Pithekoussai (or Pithecusae in Latin) near current day Naples. This port city enabled the settlers to trade with locals, creating a vast trade system with objects from Greece and the Middle East. This explains the plethora of imported goods found in various tombs and sanctuaries throughout Etruria.

Latium

Although the Etruscans did not outright conquer Latium and the surrounding regions, they did expand their control through these areas. The Etruscans were a formidable maritime power, using the sea routes to trade their mineral exports and to protect their lands from those who would wish to benefit from them. Between the eighth and sixth centuries BCE the Etruscans sailed from their native land of Etruria southwards to Campania, founding Capua as the capital there (Pallottino 1991, 70). After they had settled in Campania and established their thalassocracy, the Etruscans spread through mainland Italy to establish overland routes to their Campanian domain. The direct route from Etruria to Campania cut through Latium,

specifically along the Sacco and Liris river-valleys. The Etruscans did not seem interested in dominating the Latins; “[w]hile not obliging them to conquer the entire territory, this did imply control of the chief towns and thoroughfares” (Pallottino 1991, 72). Satricum was one of these towns (see Image 1 in Appendix D). By the first half of the seventh century the Etruscan influence had spread to Satricum. Indeed, it is possible to “think of Rome and Latium as a less wealthy region of Etruria” through the seventh century (Pallottino 1991, 81).

The end of the sixth century began a period of crisis and instability in Latium and the Greek-Tyrrhenian societies. The rise in power of Carthage and Sicily, as well as expansion by Greek colonists and the weakening of the Etruscan thalassocracy heralded the imminent decline of the Italian cultures. Sybaris, an important colony located in Magna Graecia, rose to fame and power in the early and middle of the sixth century (Pallottino 1991, 79). It was highly influential both economically and politically and was historically significant throughout the Mediterranean world. Its fall from power in 510 BCE sparked the period of unrest in Italy that lasted through the beginnings of the fourth century BCE.

From the late sixth century through to the first decades of the fourth century the archaeological record reveals far fewer artifacts than the prosperous era that preceded it. Tombs and grave-goods became less prevalent throughout the Italian peninsula as well as other western Mediterranean areas. The collapse of the Sybaris-based supremacy was felt throughout the entire region. The previously affluent and urbane society of the Etruscans saw a dramatic decrease in prosperity, possibly due

to competition in the trade of raw materials or the decline in the yield of said materials.

This time period also saw the end of the Etruscan monarchy in Rome, dating to 509 BCE with the end of the reign of Tarquinius Superbus, and the beginning of the Roman Republic, which lasted until Augustus came to power in 31 BCE. In fact, the name of Publius Valerius Publicola, one of the founders of the early Roman Republic, was found in the temple at Satricum (Pallottino 1991, 89; Fagan 1999, 15).

Post-Etruscan Latium

During the beginning of this cultural decline the nearby native peoples, known as the Volsci and Aequi, took advantage of the political weakness and expanded into Latium. Between the early fifth century and 430 BCE, Satricum, Terracina, Antium, Velitrae, Formia, and Fondi, among other colonies, were occupied by the Volscians (Pallottino 1991, 103). Due to the successful political system employed in these colonies, the Volsci and Aequi became a looming threat to Rome. Thirty of the colonies in Latium banded together for security and stability to form the Latin League in 501 BCE. In response, Rome created a treaty with the Latin League in 493, lead by Spurius Cassius, called the 'Treaty of Cassius', or the *Foedus Cassianum* (Fagan 1999, 25; Alföldi 1965, 114). The treaty was renewed in 358 BCE.

Rome was finally successful in defeating the Latins, Volscians, and Campanians between 340 and 338 BCE, during what is known as the Revolt of the Latin League. The outcome of this campaign resulted in the disbanding of the Latin League and the formation of a new Roman-Latin-Campanian league (Pallottino

1991, 178). This alliance became the basis for the formidable power that the Roman Republic and Empire was to become.

Satricum

Before a set of artifacts can be studied, it is crucial to understand the history of the site from which they came. Satricum, modern Le Ferriere, is located in Italy and the artifacts examined here are of the Hellenistic era with an approximate date of the third to second centuries BCE. Satricum was situated south of Etruria, roughly 10 kilometers from the Mediterranean Sea and 60 kilometers from Rome, in the region of Latium (Gnade 2013, 1). A map of the region is printed in Appendix D (Image 1). Satricum's proximity to Rome allows scholars to compare the relatively small amount of data of Satricum to the quite well documented history of Rome. "In fact, Rome's history during the first quarter of the fifth century seems in every way similar to that of Latium as a whole and Etruria" (Bloch 1960, 100).

Satricum's location in the lower Tiber Valley was extremely beneficial since "it is a junction for several natural thoroughfares" (Bloch 1960, 63). Being so close to the sea and in such an advantageous location gave Satricum prime opportunities for the exchange of goods and ideas. The strategic position between the Via Appia and the Mediterranean Sea gave Satricum access to an extensive trade network. It is set on a hill next to the Astura River, with sixth century BCE fortifications surrounding nearly 40 hectares (Gnade 2013, 1; Smith 1996, 138-9).

The earliest evidence of continuous occupation found at the site, small huts and burials, date from approximately 830 BCE. A central hut dating to the ninth century measured roughly 7m x 4m and may have had cult associations, while

domestic evidence from cooking areas and rubbish deposits indicate habitation (Smith 1996, 55, 87). During the seventh century evidence of the first votive deposits have been found, specifically in the area on which the Temple of Mater Matuta would later be built. Progression to stone huts occurred between the seventh and sixth centuries, as well as increased deposition of votive offerings. These offerings included some luxury items such as Proto-Corinthian pottery, Egyptian faience, Etruscan pottery and silver and gold objects. The central hut from the ninth century was replaced with a stone rectangular building, a *sacellum*, measuring 10m x 6m circa 650 BCE. The stone buildings were further expanded and reconstructed sometime during the second half of the sixth century. During this time the first stone-built temple was erected, while a second temple dates to approximately 500 BCE (Smith 1996, 253). Evidence from the end of the sixth century into the fifth century indicates a period of Volscian conquest, which agrees with the events given in various literary sources.

Three successive temples in the acropolis of Satricum were built during a period spanning 625 – 500/480 BCE (Gnade 2013, 1). The artistic influence of the Latins and Campanians can be seen in the architecture and decoration of the temples, however the strongest influence is Etruscan. The layout of the temples and other important buildings, as well as their terracotta roof decorations, are all testament to the input of these cultures (Gnade 2013, 1). This amalgamation of styles is due to the advantageous positioning of the settlement, which was easily accessible by both land and sea and therefore was in close proximity to the vast trade network of the ancient world, specifically the flow of trade goods, merchants,

and ideas from distant lands. Further proof of its strategic placement is indicated by the vast amount of votive offerings from various origins found in deposits near the temples.

Satricum is best known in history as a shrine of Mater Matuta. The main temple began construction starting in the third quarter of the sixth century on the former site of the seventh century sacellum (Smith 1996, 139). This first temple building measured approximately 8m x 21m and was replaced circa 530 BCE by a 16.5m x 27m building. The third phase of the temple, circa the early fifth century, saw a building of approximately 21.4m x 34m. This third phase corresponds with a similar trend throughout the area: “the Latin and Faliscan towns also went through a period of great activity in religious building at the beginning of the fifth century, just as Rome did; as at Rome, the character of the decoration of the Latin sanctuaries is typically Etruscan, or sometimes, as at Satricum, Etrusco-Greek” (Bloch 1960, 100). The votive deposit from this time period also indicates a strong Etruscan influence, as it contained Etrusco-Corinthian pottery as well as the typically Etruscan impasto and bucchero vessels (Smith 1996, 140).

The third phase of construction of the temple occurred during the period of Volscian invasion and occupation (see Image 2 in Appendix D). Historically it has been said that the Volsci overtook Satricum in 488 BCE and remained in control until 385 BCE when it became a Roman colony (Gnade 2013, 1). Archaeological evidence supports this claim, with three necropolises accredited to the Volscian people. An earlier necropolis from the eighth and seventh centuries is located on the northwest side of the town. Interestingly, it seems that a substantial amount of

artifacts have been found as votive deposits during this period of Volscian occupation, mostly dated from roughly 420 – 390 BCE (Ogilvie 1976, 154).

Mater Matuta

Mater Matuta, or *Matris Matutae* in Latin, is a Roman goddess, although her name is “strongly Volscian in character” and she is of indigenous Latin origin (Ogilvie 1976, 153). She is mainly considered the goddess of the ripening of grain, however she is sometimes referred to as a goddess of the dawn. She is the principal goddess of Satricum, with a temple dedicated to her there beginning in the seventh century BCE. The festival day for Mater Matuta was called Matralia was strange compared to festivals for other gods and goddesses. Only a select few were allowed to partake, namely women of free status in their first marriage, who would celebrate their nieces and nephews rather than their own children. There is some association with the sea attributed to Mater Matuta, although this is a later occurrence due to her identification with Leucothea, a Greek protectress of seafarers. Leucothea is first mentioned in the “Odyssey,” by Homer, most likely created in the eighth century but not canonized until the mid-sixth century BCE.

Satricum was not the only location of a temple to Mater Matuta. It is possible that a shrine in Rome from 470 BCE was dedicated to both Mater Matuta and Fortuna and then modified and rededicated solely in her name in 396. This shrine is located in the Forum Boarium and may have originally been consecrated by the sixth king of Rome, Servius Tullius, in the sixth century, on the site of a seventh century sanctuary. The Senate appointed Marcus Furius Camillus, a Roman leader, as dictator in 396 after a fruitless siege of the powerful Etruscan city of Veii. The

siege had started in 406 and it held until 396 when Camillus infiltrated it through the sewer system. Camillus, upon being appointed dictator, had proclaimed that if his campaigns were successful he would dedicate a temple in the name of Mater Matuta and host a celebratory games. He first conquered Falerii and Capena, both allies of Veii. He then not only conquered Veii, but also destroyed and plundered it. While unfavorable for his failure to dedicate a tenth of the plunder, which he had promised, it would seem that he held true to his promise of a temple dedicated to Mater Matuta in Rome (Plutarch, 5). Ogilvie suggests that the dedication of a temple to Mater Matuta may have been strategic, stating that this temple, “accompanied by a contemporary colony at Circeii near Satricum, points to a combined military and religious policy to win over a dangerous area. The combination of force and religion is suggestive of Camillus” (1976, 153-4). The temple lasted until 213 BCE, when, according to Livy, it burned down and was subsequently rebuilt.

The continuous modification of religious buildings, whether to rebuild after a catastrophe or as merely an updated renovation, is a significant theme throughout the history of the Italian peoples. The theme is described as “the perpetual ordering and re-ordering of the cult centre and its practices; the archaeological counterpoint to the understanding reached by religious historians of the Protean transformations of Roman belief” (Smith 1996, 100). While modern viewers may consider an ancient temple as “classic” and encompassing the stereotypical idea of an ancient temple, contemporary viewers of the temple may have seen it as anachronistic. The styles of shrines and sanctuaries were constantly changing along with the thoughts on religion. Smith concisely summarizes this view, stating, “Conservatism is a concept

out of place in both religious belief and religious building” (Smith 1996, 100), at least in reference to the early peoples of Italy.

This constant renovation can be quite helpful for archaeologists. A site that remains unchanged for centuries can be hard to date, as it may be difficult for scholars to determine if it was constantly used or abandoned for some amount of time. With the continuous changes to the buildings themselves, scholars can usually determine the rough time period for each renovation. The history of a site’s physical changes can be related to the economical and political history too. A time of prosperity and military success often is seen in the creation of new temples or rebuilding and rededicating of old ones, while a time of poverty and unrest could be indicated by a period of little construction. Between the physical archaeology, dating techniques, and literary history, a fairly accurate timeline of a religious area can often be found.

Finds

Besides the remains of temples and buildings at the site, a very large amount of votive offerings in multiple deposits has been uncovered. It was customary for pilgrims to bring an offering to a temple to show their devotion to the deity. Material goods such as money and statues were donated, as well as food and wine. Some people would bring small facsimiles of ailing body parts to ask the god or goddess to heal them. Pots and vases were a common votive offering, especially since they could be cheap, and often might contain wine or expensive oils. Some of these vessels would come from far distant lands. In a survey of over 5000 unstratified pottery vessels from a deposit at Satricum dating to the seventh century there were

approximately fifty vessels imported from Greece, which is only about 1% of the total. Contrarily, Etruscan-Corinthian pottery and bucchero vessels made up nearly 70% of the finds, with over 3500 vessels. The Greek vessels may have come from Magna Graecia or through Rome, as Satricum had no direct link to Greek imports in the seventh century. The Greek-inspired Etruscan pottery, on the other hand, is quite prevalent, indicating that there must have been “a very significant exchange between the two regions; [as] there was no reason for Etruscans to make such massive donations at Satricum” (Smith 1996, 140). The ratio of Greek to Etruscan vessels in the unstratified category indicates, at least for Satricum during this time period, that there was indeed a strong trade network with the Etruscans, while direct contact with the Greeks was more limited.

During the seventh century the Etruscans were expanding their influence from Etruria down to Campania in an overland route to their colonies. While not conquering the lands between their domains, they did instill much of their culture in the area. Rome did not feel this influence as strongly as the area of Latium until Lucius Tarquinius Priscus became king in 616. While there is little evidence of trade between Rome and the Etruscans in the seventh century, there is substantial evidence for a “flourishing trade in Greek and Italo-geometric pottery attested by the votive deposit at Satricum” (Alfoeldi 1965, 330).

2. Trade and Influence

Trade by sea was a well developed practice in antiquity. Trade networks were established thousands of years ago... Later, the Greeks traded their wine, oil and wares (mostly pottery) for Carthaginian and Etruscan metals. When subsequently Rome grew in economic and political importance, the centre of trade moved to Italy, and the Roman Empire built up a widespread trade network. (Ganio et al. 2012c, 217)

Ancient Trade

Trade was one of the most important aspects of the prosperity of ancient cultures. In the Mediterranean the trade network was enhanced by the ability of the merchants to travel by sea. Transporting goods by water was often far easier than traveling over land. The proximity of many ancient cultures to the Mediterranean Sea allowed for an extensive network.

Etruscan Art

Etruria is most famous for its art and architecture. Early pottery wares native to the area date to the eighth century BCE, and “var[y] between grey and glossy black... The Etruscans, therefore, had considerable knowledge of kiln-design” (Savage 1963, 54), which could indicate the possibility of the knowledge of glass production. Many of these pieces of art are reminiscent of those found earlier in Greece and later in Italy. “Greece was a source of inspiration, but it did not stifle all the originality of Etruria’s quite different character” (Bloch 1960, 107). During the Archaic Period small colonies of Greek merchants were founded in Etruria. Evidence of these colonies comes from epigraphical sources from Caere and Spina (Bloch 1960, 109). Artists in these colonies would have brought new technologies

and ideas to the areas. “...[S]ophisticated local artists – metal-workers, goldsmiths, gem-engravers, and so forth – produced articles inspired by the taste for eastern fashions, and here too there must have been large-scale importation of foreign ware made of perishable materials such as wood and, especially, fabrics, which have unfortunately perished” (Pallottino 1991, 68). Again, not much can be said for a majority of objects from antiquity, as many were made of perishable materials.

So why was Etruria such an epicenter of Greek activity? And how did it rise in economic and cultural prominence? It lay on the far, western coast of Italy, which was not convenient for seafarers from the eastern Mediterranean. The answer lies, as it often does in ancient societies, in the area’s resources. There were vast raw ore deposits and bountiful harvestable forests located in Etruria, which made it a prime location to control. These two materials, ore and wood, were in high demand in antiquity. The standard of wealth lay in the weight of metal; metal equaled money, regardless of the society, location, or shape. The mineral deposits in Etruria would have enticed foreign workers to emigrate there, giving “rise to a complex network of exchange, allowing a vast and ever-growing volume of foreign productions to find their way to Etruria” since “[t]he great purchasing power of the Etruscan economy, and the rich and powerful citizens’ desire for ostentation, encouraged imports from Greece and the Near East” (Pallottino 1991, 66). The samples from Satricum may have been locally made, or could have been imported from elsewhere.

Glass Trade

Unfortunately, ancient glass, especially of the Roman soda-lime-silica variety, tends to have a relatively homogenous chemical makeup and the categorization of

typology does not necessarily denote specific compositional groups. While ceramics can often be provenanced or sourced by chemical composition or typology or even an artist's signature, this proves much more difficult with glass objects. Currently, the most reliable way to determine whether glass artifacts are from the same location or batch is to study the isotopic analysis of the pieces. Isotope analysis determines the isotopic composition of the possible sources of an artifact's material, which in turn can specify the source's geographical location. As with any analysis, however, there are difficulties. The methods and issues of provenancing glass are detailed in Chapter 5.

Hellenistic Glass

Unguentaria, or small containers, were some of the first glass vessels made. Their small size was favorable for the early vessel production technology. Given that the perfumes and ointments they held were often very valuable, the vessels were often made to reflect the value of their contents. By the beginning of the Hellenistic Era unguentaria were becoming more popular, following a decline in production in the fifth century. The shapes and sizes of vessels in all materials were ever changing with the fashions of the times and often mimicked pottery forms. The Hellenistic Era saw larger alabastra and jugs, fewer aryballoi, more lentoid and hydriskai shapes, and more decoration. The feather pattern was also favored during this time (Forbes 1966, 5:130-1). The core forming technique, explained in Chapter 4, was used until the discovery of glassblowing.

The surge in glass production during the Hellenistic Age most likely stems from the flourishing of the economy due to Alexander's leadership and unification.

The glassmaking industry underwent a “renaissance” of sorts during this period, starting in the late third century until the beginning of the Roman era (Grose 1989, 185). Alexandria, one of the most important cities founded by Alexander, became a forerunner of the glass production industry. Alexandria specialized in mosaic glass canes, as well as molded, enameled, and engraved glass. By the time glassblowing was discovered Alexandria was one of the most important producers of glass in the Mediterranean world.

Production Sites

Focusing on the third century BCE, or Hellenistic Period, of the Roman era, there is a dearth of primary production sites. In fact, “for the period between the eighth and the first centuries B.C., no archaeological evidence of primary production sites has yet been found” (Henderson 2013a, 94). This is not to say that the regions conquered by the Romans, Italy in particular, had no furnaces. Glass furnaces have been found from the relative time period in England, Germany, and France, so with the conclusion that Roman Britain and Europe had glassmaking, it is logical to assume that there were other production sites elsewhere in the areas occupied by the Romans.

Of the sites that have been encountered, a variety of furnace shapes have been discovered. Square, rectangular, and round kilns are common, depending on the culture and technology of the workers during that time period and the materials at hand. Some Medieval furnaces were built on the model of a beehive, allowing the top level to be used as an annealing oven while the bottom level was the firing

chamber (Agricola, cited in Henderson 2000, 41). It is possible that the medieval furnaces were modeled after ancient kilns of a similar shape.

Glassblowing

Once glassblowing was introduced the availability of glass objects increased dramatically. With glassblowing the artist was able to quickly produce far more vessels than ever before. The technology made production faster and simpler; the artisan merely had to blow a glob of molten glass into a mold rather than using the earlier core-forming or casting techniques. As with any craft production, the ease of creation led to a decline in price and exclusivity of the product. For so long glass vessels were held in high esteem, but once glassblowing technology spread the vessels became accessible to the lower classes. No longer were glass vessels considered a luxury; while the highly decorated and colored unguentaria were still considered valuable, the mass-produced blown vessels were relatively cheap. Blown glass vessels were “becoming a common medium for table-wares, with a value moving towards that of pottery” (Fleming 1999, 13) and could be found in households of any social status.

Roman Glass

To further elucidate the effect of the Greeks on the Roman world, many aspects of glass technology are similar.

Chemical analyses of Roman glass dating to as early as the first century B.C. apparently show that there is little compositional difference from the contemporary late Hellenistic glass. This is hardly surprising given that the Romans were influenced so heavily by the Greeks with a probably continuity in glass production on the Levantine coast. The possible primary production centres for early Roman glass are the Levant, North Africa and Italy. (Henderson 2013a, 247)

Again, no primary glass furnaces have been discovered dating before the first century BCE, but scholars are becoming more confident in the possible locations of these sites.

There has been much research done on Roman glass. The majority of Roman glass, as with most Hellenistic glass, is in the soda-lime-silica category. Soda-lime-silica glasses are characterized by approximately 2.5% alumina, 6 – 8% calcium oxide, and less than 1.5% magnesia and potassium and are characteristic of glass from the Mediterranean from c. 800 BCE to the ninth century CE (Aerts *et al.* 2003, 659; Shortland and Schroeder 2009, 954). The fact that this general composition is found in glass artifacts throughout the Mediterranean and there is only a “small range of compositional variation... produced over a long period (800 years or more)” (Aerts *et al.* 2003, 659) is quite extraordinary. This homogeneity of results is remarkable, but makes it far more difficult to quickly determine an object’s provenance.

PART TWO - Historical Background and Science of Glass

3. Ancient Glass Technology

Science of Glass

Glass is an amorphous solid, meaning it has no crystalline structure. It is also classified as a super-cooled liquid. The main component is silica, or SiO_2 , as the network “former”. It is combined with other metallic oxides in various concentrations, depending on the type and color of the glass. A modifier, or flux, is necessary to reduce the melting temperature; the most common modifier was soda, or Na_2O , which “bonds ionically with oxygen within the network and disrupts bridging atoms within the silica tetrahedral network” (Henderson 2013a, 2-3). Pure silica glass is possible, but it has a melting point near 1720°C , which is much too high a temperature for ancient man to achieve. Soda reduces the melting point to about 1150°C , a far more obtainable temperature. Silica glass with only a modifier such as soda is also possible, but glass formed with only those two components is soluble in water, which is an undesirable trait in a material that was often used to hold liquids. The third main component in most glasses is a network stabilizer. Calcium oxide, or CaO , was one of the more popular stabilizers. The most commonly created glass in antiquity was the soda-lime-silica glass, comprised of silica (SiO_2) as the former; soda, or sodium oxide (Na_2O), as the modifier; and lime, or calcium oxide (CaO), as the stabilizer (Henderson 2000, 25; 2013, 2-3).

When the correct ratio of raw materials is heated, the batch will become molten.

At about 1400°C the entire mixture fuses into a viscous liquid. The temperature is then held steady for some hours; it is lowered (to $1100 - 1300^\circ\text{C}$) towards the end

of the operation to raise the viscosity of the batch so that it is ready for manufacture into artefacts. This has to be a relatively quick process, at most a matter of minutes, as the cooling glass changes rapidly from a highly viscous liquid to a solid. (Moorey 1994, 203)

Depending on the ratio of raw materials, the period of time during which the molten glass can be easily worked varies. For example, Egyptian glass during the Hellenistic period (c. 300 BCE – 50 CE) had a lower than average lime content and higher than average silica content. This would have made the glass easier to blow when glassblowing came into use (Forbes 1966, 5:117).

The exact science behind the production of glassmaking was not completely understood by artisans until quite recently, relatively speaking. Trial and error would have been prevalent in the glassmaking community, specifically in regards to ratios and sources of raw materials. Some sand was known to produce a clearer glass than sand from other regions; while the ancient glassmakers may not have known why, scholars can now explain that the preferred sand must have had fewer impurities, specifically of iron. “In common with glassmakers until modern time, when chemical reactions could finally be analysed and controlled, they appear to use redundant materials and excessive care, simply because they could not distinguish precisely the effective from the ineffective” (Moorey 1994, 203).

Oral tradition would also have played a large part in the knowledge of the technology. The *chaîne opératoire*, or sequence of steps in the production of an artifact, was a well-guarded secret, with the information passed from master to apprentice. At the beginning of the history of glass production, ritual and magic were highly involved. As the “first truly synthetic material” (Henderson 2013a, 364) and often used to imitate highly prized precious stones, it is no wonder that glass as

a material and the technology behind it would be steeped in ritual. The secrecy surrounding the production of glass further accounts for the lack of primary sources providing insight into the technology.

Impurities

While the oxides mentioned above are the basic components of most ancient glasses, glassmakers in antiquity would rarely have had access to pure forms of these substances. Impurities were commonplace and would change the outcome of the batch of glass. Sometimes the impurities were helpful; in some sand sources there existed an abundance of crushed shells, providing the necessary calcium oxide to modify the batch without needing to add lime separately. Mostly, however, the impurities were a hindrance, specifically in regards to the color. The most common ‘negative quality’ impurity was usually found in the sand source, this time in the form of iron. The iron in the sand would tint the glass a greenish blue, which was not desirable if the maker was trying to attain clear glass. In the case of impurities changing the color of a batch of glass, other elements, such as manganese, could be added to counteract their effects. As ancient craftsmen would not have known about the specific scientific reasons behind the effects of various materials on the outcome of any given batch of glass, trial and error must have been the main process through which glassmakers perfected their art.

Raw Materials

Before a glassmaker could refine his glassmaking process, the raw materials would need to be acquired. This in itself could prove difficult. Silica is readily

available in sand from a beach or river, quartz pebbles, and geological deposits (Henderson 2013a 309); this would have been relatively easy to obtain. As stated before, however, iron was often found as an impurity in sand. So while silica might have been easy to obtain, *good* sources of silica may have been harder to come by. Other impurities often found in sand include feldspars, titanite or sphene, chromite, chromium or epidote, olivine, ilmenite, mica, calcite, and zircons. These could have added alumina, calcium, sodium, potassium, iron, chromium oxide, and titanium oxide as chemical impurities (Henderson 2000, 27; 2013, 60).

The flux was either plant ash or natron. Between c. 800 BCE and 800 CE, natron was the main source of flux in the form of sodium bicarbonate. Natron is a naturally occurring material that is comprised of the leftover alkali salts from an evaporated salt lake, named for Wadi el Natrun, the area in Egypt where it was most readily found. It is mainly sodium carbonate decahydrate ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$) and analyses have shown it can be comprised of 22.4-75% sodium carbonate and 5-32.4% sodium bicarbonate, with 2.3-29.9% sodium sulfate and 2.2-26.8% sodium chloride as impurities (Henderson 2000, 26). Upon heating, in a process called *thermal decomposition* or *thermolysis*, the natron creates Na_2O (sodium oxide or *soda*) and CO_2 (carbon dioxide).

The stabilizer was provided by calcium oxide in the form of lime. Lime, when heated, also undergoes thermal decomposition, releasing carbon dioxide: $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$. Calcium oxide was added to a batch by way of limestone or as crushed shells in the sand providing the batch's silica.

After the raw materials have been chosen, the ratios must be perfected. Too much of any one component will throw off the stability of the final product. Too little of the stabilizer would make a material that is soluble in water, while too little of a modifier will produce a batch that doesn't fully melt, as the melting point would be too high for the furnaces to reach.

Colors

One of the most striking characteristics of glass is its vibrant coloring. The entire spectrum of the rainbow is possible, both in opaque and transparent variations, along with black, white, and the entire gray-scale. The color of glass depends on the materials it is made of. Glassmakers from an early stage learned how the addition of some compounds changed the resultant color. The Egyptians preferring opaque turquoise, white, and yellow, while Roman glass is often characterized by a blue-green tint to its transparency. This is due to the presence of iron oxides found often as impurities in the sand used as the silica source. The addition of small amounts of manganese in a reducing atmosphere was discovered to have a decolorizing effect to iron-tinted glass, but the addition of too much manganese or an oxidizing atmosphere would turn the batch purple (Fleming 1999, appendix A, 141). Antimony was often used as an opacifier. Other compounds used as coloring agents include oxides of gold, copper, iron, manganese, arsenic, antimony, and cobalt (Moore 1935, 9-10). The levels of these compounds directly influenced the resultant color and often only minute levels of the compounds were required to color a batch. The table below shows some of the most common

colorants and the required furnace atmosphere (Fleming 1999, appendix A 140-4; Forbes 1966, 9:136; Harden 1956, 312-4; Henderson 2000, 30-8).

Metallic Oxide	Common Minerals	Furnace Atmosphere	Color
Cobalt	Cobaltite $(Co,Fe)AsS$ Skutterite $(Co,Ni,Fe)As_3$ Trianite $2Co_2O \cdot CuO \cdot 6H_2O$		Blue
Copper	Cuprous Oxide (Cuprite) Cu_2O	Reducing	Red
Copper	Cupric Oxide CuO Azurite $Cu_3(OH)_2(CO_3)_2$ Chrysocolla $CuSiO_3 \cdot 2H_2O$ Chalcopyrite $CuFeS_2$	Oxidizing	Blue to Green
Iron	Ferrous Oxide FeO	Reducing	Green
Iron	Ferric Oxide Fe_2O_3	Oxidizing	Amber
Iron + Sulfur		Reducing	Amber
Iron + Manganese			Orange
Manganese	Pyrolusite MnO_2	Oxidizing	Purple
Manganese (small amounts)	Pyrolusite MnO_2	Reducing	Clear (Decolorized)
Arsenic	Arsenic Trioxide As_2O_3		Clear to White
Antimony	Antimony Oxide Sb_2O_3 Stibnite Sb_2S_3	Oxidizing	Clear to White
Antimony (small amounts)	Stibnite Sb_2S_3		Clear (Decolorized)
Antimony + Calcium	Calcium Antimonate $Ca_2Sb_2O_7$		Opaque White
Antimony + Lead	Bindheimite $Pb_2(Sb,Bi)_2O_6(O,OH)$ Lead Pyroantimonate $Pb_2Sb_2O_7$		Opaque Yellow
Tin	Cassiterite SnO_2		Opaque White
Copper + Manganese			Black
Iron (large amounts)		Reducing	Black
"Egyptian Blue"	Cuprorivaite $CaCuSi_4O_{10}$		Turquoise

Cobalt

Cobalt is of special interest in this paper, as most of the samples analyzed were a deep blue color attributed to the presence of the mineral. Only a small amount of cobalt, less than 2%, is necessary to produce a dark blue color. Some possible locations from where the ore may have originated are the Caucasus region and Iran (Lucas 1934, 218). Traces of cobalt may have been present in Egyptian copper ores, which would have produced a more vibrant blue color if added to a batch than pure copper would.

Copper

Copper was mined throughout Egypt and most of the Mediterranean world and was extracted from ores by smelting. Some pre-Roman era locations of copper mines include Spain, Portugal, Cyprus, Serbia, Russia, Austria, and many areas in Italy, specifically Tuscany (Forbes 1966, 7:154-7). Copper, even after it was smelted and refined, often had traces of antimony, lead, gold, silver, nickel, tin, arsenic, zinc, sulfur, silver, and iron (Forbes 1966, 9:36).

Iron

Iron is often present in a batch of glass as an impurity in the sand source, but other sources include meteoric iron. Meteoric iron is distinct from iron ores as it contains roughly 5-26% nickel, although usually only 7-8%, and 0.3-5.0% cobalt (Forbes 1966, 9:189; Lucas 1934, 193). While meteoric iron is not as abundant as iron veins, theoretically it could be found anywhere. Iron mines have been found in Italy, France, Germany, Bosnia, Egypt, Mesopotamia, the Caucasus, and other areas around the Aegean (Forbes 1966, 7:155; 9:193-5). A significant mine in Italy was located on the island of Elba, which was controlled by the Etruscans and was one of their most important resources.

Tin

Tin collection has been attributed to areas in France, Turkey, the Caucasus region, and Italy, again specifically Tuscany (Forbes 1966, 7:155). Stream tin, or tin deposited in alluvial gravels, was often used, especially since gold can also be found in streams. Alluvial tin has a higher concentration of tin than the vein ore, as the

natural washing mechanism in the streams removes many of the impurities (Forbes 1966, 9:138).

Antimony and Arsenic

Although both elements can be found in analyses of glass objects, it is unlikely that they were mined and prepared in antiquity. Ores of both elements were known and used by ancient craftsmen, but there is little evidence to support a widespread production of either element (Forbes 1966, 9:171). Stibnite (Sb_2S_3) can be found in France and China, and deposits in lead ores have been found in Asia Minor, ancient Persia, India, and even Japan. Since arsenic was not likely to have been intentionally produced in the ancient world, its presence in glass must be attributed to impurities in other compounds, specifically copper and iron. Arsenic did have a few applications in antiquity, however; it was known as a pigment and was used as a poison and for medicinal purposes. Arsenic compounds were found in Persia and the Caucasus (Forbes 1966, 9:179).

Working

Next in the production cycle would be the working of the glass. There are many opposing ideas as to how the production cycle of glass worked; unfortunately, the lack of clear evidence has left the topic unanswered. Some production sites may have made vessels and objects straight from the molten batch of raw materials, but this seems unlikely. The more common thought is that the glass from the glassmaking sites (called *primary production sites*) would be sent to secondary

workshops where the raw glass, often in the form of ingots, would be remelted and worked.

Annealing

Finally, any molten or heated glass must be allowed to cool slowly to avoid stress within the material. This process is called *annealing*. Annealing is crucial to the creation of glass objects, since molten glass that cools too quickly will crack. Molten glass is liquid and solid glass is considered solid, but is technically a super-cooled liquid or an amorphous solid. While regular solids have a crystalline structure, amorphous solids have a random structure. The molten glass must be allowed to cool down slowly, allowing for the internal stresses to release (Bray 1995, 26). The surface of glass cools much faster than the interior, since it is exposed to the surrounding atmosphere, creating tension that can result in cracking. Heated glass must be allowed to cool slowly and evenly. The time required for an object to fully anneal depends on the “thickness, nature of the glass, its coefficient of expansion, the amount of surface exposed and the amount of residual stress required” (Bray 1999, 26). These criteria dictate the amount of time an object must be held at the temperature called its *annealing point*. After this period of constant temperature the object is slowly cooled to room temperature. Again, given the lack of scientific understanding of these specific concepts, glassmakers of antiquity would have relied on trial and error to perfect this method.

Furnaces

An important thing to consider in the process of glassmaking is the furnace. Although the flux would reduce the melting point of the silica from 1710°C, the batch would still need a temperature of at least 1100°C to melt the materials (Henderson 2013a, 5). Furnaces from the Eighteenth Dynasty in Egypt, circa 1500-1300 BCE, the time period for the beginning of glass vessel production in Egypt, could not quite reach the required 1100°C required, causing the glass objects to often be opaque or opalescent (Harden 1956, 312). Ancient ceramic furnaces could reach a temperature of 1050 – 1150°C, while open-air campfires could only reach 700 – 800°C (Forbes 1966b, 70). The shape and structure of the furnace, along with the types of bricks used, would have affected the temperature range. It is thought that some furnaces must have been able to reach 1400°C, as 1100-1400°C is the temperature range required to melt a batch of soda-lime-silica glass (Henderson 2000, 30). While some *glassworking* furnaces have been discovered, there are inordinately few that can be proved to have *made* glass.

To properly make a batch of glass from the raw materials, an appropriate furnace must be available. Different shapes and styles of furnaces have been used through the centuries, but they all have the same basic characteristics. The most important criterion is that they must be able to achieve temperatures high enough to melt the raw materials. An opening through which to feed fuel is required, along with proper ventilation that contained the heat of the fire. Sometimes an annealing oven was built separately from the main furnace, but to conserve the heat a section of the main furnace was often partitioned for annealing. An opening into the main

chamber of the kiln, called a *glory hole*, was built to allow the insertion and removal of crucibles, as well as letting the glassmaker inspect the batch throughout its progression.

There are two main types of furnaces for glass production: *tank furnaces* and *pot furnaces*. Tank furnaces, like those found in Beirut (examined in Chapter 7), were furnaces that utilized the entire volume inside the kiln as the receptacle for the molten glass. Pot furnaces used crucibles or pots to hold the molten glass. After the glass solidified and cooled, the ingots would be pulled out, chipped out, or the crucible would be broken off. Pot furnaces were preferred for small batches of glass, especially when multiple batches of different colored glass were desired.

Unfortunately there “is no information in any ancient author concerning the furnaces, crucibles, and other tools of the glass-maker’s trade in antiquity” (Harden 1956, 332). Some of the earliest literary sources of glass production are from *Schedula diversarum artium*, by the monk Theophilus, circa 950 CE, and *De coloribus et artibus Romanorum*, by Heraclius, from around the same time. As Harden proclaims, “[i]t is very remarkable that medieval texts should be our basic literary sources for the composition of glass of 1500, and more, years earlier” (Harden 1956, 329). Considering there are currently no primary literary sources on ancient glass production and the technology seems to have remained constant throughout the millennia, the medieval texts are the closest evidence scholars have for descriptions of ancient furnaces. Some of the medieval sources describe a three-tiered beehive-shaped furnace structure, consisting of a fuel chamber, pot chamber, and annealing oven, from bottom to top. There is no evidence to conclusively prove or disprove

that furnaces of this shape were used in antiquity, however it seems that a furnace found in Corinth may have been built in the same way (Harden 1956, 332).

While production and technology of glassmaking changed between its discovery and the end of antiquity, it seems that the basic technology remained fairly constant. Besides the change in flux (natron to plant ash) in the 9th century CE, little else seems to have changed. Therefore although it is not optimal, it could be argued that the medieval procedures may have been similar (if not identical) to those in antiquity.

Workshops

Glassmaking workshops would arguably have needed to be near to the raw materials or ports where the materials could be obtained for them to be realistically productive. Antonaras claims that workshops could also have been located on estates of wealthy officials in the western provinces of the Roman Empire, due to analogies with the metal, pottery, and brick-and-tile workshops (2012, 4). In the eastern provinces, however, “it is more likely that glassworking workshops were small-scale individual businesses that could collaborate freely and form partnerships according to their interests, as demonstrated by vessels that were blown in identical molds but bear the names of different glassworkers” (Antonaras 2012, 4). This hypothesis refers to the time after glassblowing was introduced, but could very well have been true for the prior centuries.

The discovery of glass ingots, specifically at the Ulu Burun shipwreck, provides arguments for the separation of primary and secondary workshops. There may have been some large primary workshops that produced only ingots, which

were then traded to secondary workshops where the ingots were melted down and worked. If this were the case, only the primary workshops would need to be located within close proximity to raw materials or a large trading area. The secondary workshops could theoretically be placed anywhere, although it would need to be in a location that had access to enough fuel to run a furnace. Although the Ulu Burun shipwreck dates much earlier than the Hellenic-Roman period, it can be argued that these long established trade routes would have continued through this prosperous period.

4. History of Glass

Origins of Glass

Natural glass has existed since the beginnings of Earth. The most common occurrence of natural glass is in the form of obsidian. Obsidian is created when silica-rich stone is melted into magma and then cooled rapidly, specifically when the lava from a volcano meets water, snow, or ice (Doelman *et al.* 2012, 100). This rapid cooling process is known as *hyaloclastic*, from the Greek words “*ὑαλος*”, meaning “glass” or “glassy material” and “*κλαστός*”, meaning “broken into pieces”. Lightning striking a beach also can create natural glass from the fusion of the silica under intense heat. The non-crystalline structure can be defined as an “undercooled liquid with a very high viscosity” (Forbes 1966, 5:114).

Bead making is arguably one of the oldest crafts in human technology. The earliest glass bead known so far is from Syria and dates to the early third millennium BCE (Henderson 2013a, 133), however the similar technology of glazing occurred around or earlier than 4000 BCE (Harden 1956, 311). The advent of true glassmaking and working appeared circa 2500 BCE in the form of simple beads and small objects. Glass vessels began to be created circa 1500 BCE (Nicholson *et al.* 1997, 143). The invention of glassblowing was not introduced until approximately 50 BCE (Henderson 2013a, 251). Before that the resultant glass objects were dependent on a few limited techniques.

Technology	Beads from artificial materials	Faience	Glazed steatite beads	Faience vessels	Glazing
Time Period	Mid-sixth century BCE	~ 5400 – 4300 BCE	Last quarter of fifth millennium BCE	End of fourth millennium BCE	~ 4000 BCE
Location	Mesopotamia	Mesopotamia	Egypt		

Technology	Glass beads	“Egyptian Blue”	Glassmaking – beads and small objects	Glassmaking – vessels	Glassblowing
Time Period	Early third millennium BCE	2550 – 2400 BCE	~ 2500 BCE, 2465 – 2323 BCE (Fifth Dynasty)	~ 1500 BCE	~ 50 BCE
Location	Syria	Egypt or Mesopotamia		Egypt	Levant

(Moorey 1994, 166-215)

A story by Pliny the Elder recounts how a group of sailors may have discovered the technique to make glass. They camped on the beach of the River Belus, and, being unable to find stones to support a pot to prepare their dinner, used blocks of natron (alkali salts commonly used in creating ancient glass) that they were transporting in their ship. The natron melted and mixed with the sand in the heat from the campfire, producing glass (1855, XXXVI 65). This is highly unlikely to have been true, as glassmaking was more likely a byproduct of trial and error in glazing, faience-making, and metallurgical processes than a simple accident on a beach. Plus, the temperature in a campfire is not high enough to fully melt the materials into glass. Although Pliny was mistaken that this was the origin of glass, he was correct in noting that the sand of the River Belus was most likely used in glassmaking for a long period of time.

Vessels

The technology to make glass vessels seems to have appeared quite rapidly in Egypt around 1500 BCE (Nicholson *et al.* 1997, 143). During the reign of Tuthmosis III, dated c. 1479 – 1425 BCE, the technique of glassmaking suddenly emerged, giving rise to speculation that glassmakers may have been imported to Egypt from Mesopotamia during the pharaoh's campaigns. From this point on, Egyptian artisans started producing mostly small vessels to hold ointments, perfumes, and pigments (Peck 2013, 159). These early items were reserved for the highest members of society and were most likely made in specialized workshops. Glass vessels, until glassblowing allowed for different forms and quicker production, were often small, luxury items that were made as “prestige packaging for precious oils or unguents, or for special use as tableware” (Moorey 1994, 195). The definition of a luxury item will be discussed later in this chapter.

Core Forming

One of the earliest techniques of making glass vessels is the core forming technique. A core of friable material, especially plants, sand, dung, or clay, was molded onto a stick in the shape of the desired vessel. This core was then either dipped into molten glass or had the glass trailed over it in a spiral until it was completely covered. Once the glass was in the desired shape it was left to cool. After it had cooled the core was burnt or dug out, leaving a hollow space inside the vessel. Given that this was the most common method of vessel production before

glassblowing it is most likely that this was the technique used to create the Satricum samples.

Slumping

Slumping is a technique where a flat piece of cooled glass is laid over a concave or convex template and placed in a furnace. As the glass plate warms up and becomes less rigid, gravity will allow it to relax downwards into or onto the shape of the mold. The mold may be decorated with incised patterns to give the final product a patterned design. This technique is most effective for making bowls and shallow dishes rather than small vessels.

Molding

This technique is also used in metalworking. A mold is created and the molten glass is poured into it. Once allowed to cool the mold is broken open to retrieve the object. This technique is useful for making small ornaments or inlaid pieces, but is not very good for making vessels, as vessels by definition need to be hollow. Creating a hollow piece in a mold can be quite difficult.

Casting

Another technique best used for making bowls or small objects is casting. Although similar to molding, casting is most effective for glass that is not heated enough to be molten. A mold is used and cullet, mosaic pieces, or chunks of raw glass are placed in it. An open mold was best for pendants and inlays. A two-part mold for casting was used to create bowls; the raw glass was placed into the bottom of the concave mold and a second mold piece was placed on top. This second piece

was convex and would create the inside wall of the dish. The raw glass was essentially sandwiched between the two mold pieces and when heated would flow to conform to the given shape (Wight 2011, 16-7).

Decoration

The most common decoration of the early glass vessels occurred during the object's initial creation phase. While still molten and on the stick, when using the core-formed method, the artist would drizzle a fine thread of a different colored glass around the object, most often in a spiral. Before it was allowed to cool, the artist could drag a small tool in lines perpendicular to the trailed color. Depending on the direction, length, and amount of these pulled lines the resultant decoration could be a wave, feathered, or chevron design. This combing method was the most popular type of decoration of early glass vessels. The rims and bases of these early vessels could be added on as extra globules of glass or pulled from the main body using heat resistant tools. Handles were most often added as extra glass after the body was created (Peck 2013, 160).

The other main type of decoration was favored during the Roman period and is termed *mosaic glass*. As the name implies, mosaic glass was created by placing small pieces of glass in a deliberate pattern and fusing in a kiln. Often used with the casting or molding techniques the glass pieces would be placed in the bottom of the mold. When heated the pieces would fuse together, creating a solid object. Solid colored glass pieces could be used, as could decorated cane pieces. Canes of glass could be wound together to create a spiral design, or placed together to create a pattern or image. The artist would be able to create the image by attaching different

colors of glass cane to each other in the desired pattern. This larger cane would then be heated and stretched. As the cane is lengthened the diameter would become smaller, shrinking the image but keeping the detail. Once the appropriate size was accomplished the cane would be cut into small slices to be used as standalone beads or tesserae for the creation of mosaic glass objects. The slices of cane could be arranged in the bottom of a mold and cast, or could be adhered together in a flat plate and later slumped to make a dish (Wight 2011, 39-42).

Hellenistic Vessel Shapes

It is only by having a good sense of Hellenistic shapes and decorations that we can recognize how influential they were as prototypes for all the important sectors of the Roman glass industry, and how much technical change that industry underwent during the Imperial era. So let us pause for a moment and anticipate to some extent the coming few decades, ones in which there would be a revolution in the glassworking craft, both in terms of its technologies and in terms of where it would find important niches in Roman daily life. (Fleming 1999, 13)

Early vessel shapes were dependent on the technologies available to the artisan. The core-forming technique limited the size and shape of the resultant vessel. Because of this, many of the first vessels were “carrot” or “lentil” shaped, relying on the marver to adjust the size. They were often bulbous and sometimes flat. Various techniques developed over time allowed the artist to expand the range of possible shapes, and until glassblowing was invented these shapes were fairly restricted. Decoration often became the highlight of an object, with techniques such as millefiori and engraved decorations.

While the Etruscans added their own unique style to the Greek influence of pottery, such as the striking black bucchero vases, the Greeks had long established certain vessel forms that remained popular in the areas they influenced. The idea of

the Greek symposium, or dinner party, was such a crucial part of their customs that particular vase shapes were created specifically for the (often elaborate) events. Although some vessels were created for the transport of materials, their most common purpose was for daily use in a household. While vessels of daily use may have been cruder and less decorated than fine wares saved for special occasions, it is logical to assume that they most likely would have been the same shape for the same function. As Savage says, “most Greek vase shapes are variations on a well-defined prototype” (1959, 51). Some of the names of certain vessel shapes may not be the same name given by the original users; archaeologists often refer to some shapes based on their assumed intended use. The three samples from Satricum that have an identified shape are described as amphoriskoi, oinochoi, and alabastra, all of which are Greek vessel shapes.

Categories

Donald B. Harden and David F. Grose have built upon each other’s and Paul Fossing’s work to define categories of typology for ancient core-formed vessels of the first millennium BCE. The five groups, widely adopted and accepted by scholars, are:

Group	Name	Dates (Harden)	Dates (Grose)
I	Mesopotamian Group	7 th to earlier 6 th century BCE	
II	Mediterranean Group 1	Mid-6 th to early 4 th century BCE	Late 6 th to early 4 th century BCE
III	Mediterranean Group 2	4 th to early 3 rd century BCE	Mid-4 th to late 3 rd century BCE
IV	Mediterranean Group 3	3 rd to late 1 st century BCE	Mid-2 nd century BCE to first decade of 1 st century CE
V	Italian Group	Late 7 th to 4 th or early 3 rd century BCE	

Groups I and V are distinct from the middle three categories and groups II, III, and IV, are mostly referred to as Mediterranean Groups 1, 2, and 3, respectively. The Mediterranean Groups are distinct from the Mesopotamian Group; the Mesopotamian Group does not seem to exist after the 7th century BCE and the Mediterranean Groups are not found before roughly 550 BCE (Harden 1981, 51).

These five categories are based on chronology and typology of the artifacts, but given the durability of many glass objects it can be difficult to distinguish which group an artifact belongs to. Throughout the first millennium BCE, “successive changes in design and distribution almost certainly indicate the rise, from time to time, of new centres of production” (Harden 1981, 51). For example, during the Mediterranean Group 1 (MG I) phase the associated vessel forms were found in high abundance on Rhodes, leading Harden to suggest that Rhodes may have been the main primary production site of glass objects. On the other hand, the majority of Mediterranean Group 2 (MG II) vessels were found in Italy, suggesting that the main centers for production were located there. Near the end of the 4th century BCE the main production centers may have moved to Alexandria and the specificity of a single major production area for Mediterranean Group 3 (MG III) becomes less clear (Harden 1981, 53). While most likely not a major production site, there is evidence of court workshops in Mesopotamia dating to the Achaemenid Period, circa 550 – 320 BCE, which coincides with Mediterranean Group 2. These vessels “were made in a standard repertory of forms, usually copying the shapes of tableware manufactured in precious metals” (Moorey 1994, 201).

The samples from Satricum coincide with Harden's MG III, although they may be categorized as MG II if using Grose's categorization. The MG II artifacts may have come from primary production centers in the Levant and Cyprus. Harden and other scholars believe that the main center of production during the MG III era was in Italy, specifically Magna Graecia, but may also have been occurring in Macedonia (Grose 1989, 116). If we are to believe the idea that most glass vessels were produced for local use and not for widespread trade, just as "[m]uch fine pottery never strayed far from its place of manufacture and the majority is to be found in its home town or in neighboring areas" (Sparkes 1991, 134), this could be conjectural substantiation of at least some of the Satricum samples having been produced in Italy.

Production

The beginnings of glass technology occur around 2500 BCE, most likely in Mesopotamia. Glass vessel technology appeared in Egypt around 1500 BCE and continued to flourish until roughly 1070 BCE. 1070 BCE is the rough date given to the end of the New Kingdom and the beginning of an era of social and economical collapse of Egyptian cities and states. During this time it seems that glass, along with other "luxury" items, ceased to be produced, or at least were much less prevalent than before. "With the collapse of the most advanced technologies in lands bordering the Mediterranean, systems of production and distribution were shattered, and all luxury items, including glass, were severely affected" (Whitehouse 2012, 18-20).

Glass came back into production in the late eighth century BCE. While the vessels produced varied from their predecessors, the technology of production remained the same as before. This revival could indicate that glass production did not completely disappear during the three hundred year hiatus. From this revival the technology of production spread throughout the Mediterranean.

Although the technology most likely was created in Syria or Mesopotamia, Egypt is arguably the most important area in which glass developed. Small vessels from Egypt during the period of resurgence have been found in Cyprus, Greece, Syria, Mycenae, and other regions. These areas also may have had early glass production sites, as vessels similar to the Egyptian ones but of different provenance have been discovered (Forbes 1966, 5:130). Vessels possibly made in Mesopotamia have been found in eighth and seventh century BCE Etruscan graves; it is thought that the Phoenician trade network was responsible for the transportation of glass wares (Forbes 1966, 5:130).

While different workshops may have each produced a certain, specialized craft, it seems likely that workshops may have been constructed close together. Glass production makes use of a furnace, as do faience and pottery production. All three crafts can use pigments, the creation of which is itself another industry. Specifically these four industries, the production of glass, faience, pottery, and pigment, “may have been located together since they shared similar technologies and used cobalt as a colorant” (Nicholson *et al.* 1997, 146; 152). These workshops were often located in or near a temple or royal palace, “where a whole range of artisans would have been working in close proximity, sometimes in the production

of one and the same object incorporating metal, glass, and glaze as well as many other materials” (Moorey 1994, 195). Furthermore, glass production can be related to metalworking. Both require “hot technology”, or the working of a material while it is in a molten state. In this way glass production is much more akin to metalworking, since faience, pottery, and pigment production are all “cold technologies” (Moorey 1994, 195).

Although glass working can be dated to circa 2500 BCE in the form of beads and small objects, there is no evidence for glassmaking in Greece during the Bronze Age (Burns 2010, 124). However, glass objects found from the Mycenaean Late Helladic I period, circa 1700 – 1500 BCE, suggest that local craftsmen created objects from imported glass. Chemical analyses on said objects have revealed that the raw glass was imported from a variety of different locations and mixed, which may have been due to the desire for different, specific colors (Burns 2010, 124-5).

Until the advent of glassblowing in the first century BCE, small core-formed vessels were the most popular glass objects, specifically intended for perfumes, oils, and cosmetics. “By this time, these objects were produced in such quantity that it is clear that, in this part of the world, glassware, although still highly regarded, had ceased to be an exclusively luxury item” (Whitehouse 2012, 24). Glass only seems to have been demoted from “luxury item” status as the technology spread and became more available. During the third century BCE, Egypt and Syria became two of the largest exporters of glass (Lewis 1983, 134). “Throughout the Greek period, glass vessels were luxury items, mainly because their production was a highly skilled and slow process, and therefore costly” (Adkins 1997, 182). However, once enough

artisans acquired the information, skill, materials, and workshops to make glass in larger volume, especially with the advent of glassblowing, its value decreased.

Luxury Status

The main “luxuries” that ancient Greece valued were gold, silver, ivory, and purple (Vickers & Gill 1996, 33). While finely painted ceramic vessels may have been highly admired, pottery was on no level close in value to that of the precious metals. “Value is ‘worth, desirability, utility’” (Rasmussen & Spivey 1991, 138) and is subjective to the cultural fashions of the time period. Glass has often been referred to as a ‘luxury item’. But what constitutes a ‘luxury’? Wallace-Hadrill highlights the difficulty of providing a definition: “There can be, that is to say, no absolute standards of luxury, only standards relative to the availability of given commodities within a society” (1994, 145). Furthermore,

...it is essential to focus on luxury as a social process rather than on the individual items that may be categorized as “luxurious.” As a social process, luxury functions as the attempt to mark or assert a place within a network of social relationships by the display or consumption of material goods; in this process, the goods are valued in proportion to their relative inaccessibility outside the social circle that is employing them... It is precisely its potential to provoke imitation that defines a luxury, yet the more it is imitated, the less luxurious it becomes. It is only over the passage of time that luxury can be apprehended. The luxury is defined both by its novelty (and thus restricted access) and by the demonstration of its power in the growing spread of imitation. It therefore requires continuous innovation. (Wallace-Hadrill 1994, 145-6)

An item’s “potential to provoke imitation” is the basis of the idea of skeuomorphism. While an item that is considered luxurious may be unavailable to lower classes, an imitation of the object in a cheaper material will often occur. Many glass objects were the same shape and served the same function as clay objects, but merely the fact that they were made from glass gave them a status as a ‘luxury item’.

From the beginnings of glass production history through the Hellenistic period glass was considered a luxury. Creating glass objects took time and labor; an artisan must be technically proficient to work glass properly. Often the recipes and techniques of the glass industry were kept secret, being passed down from expert to apprentice or father to son. Tableware seems to have begun being made of glass in the early Roman period. These first dishes and goblets were often monochrome, sometimes the translucent blue-green color so characteristic of Roman glass. Since glass working was not yet commercialized these tablewares would have been luxury items for the elite, “in much the same way as was the black and red-figure pottery of sixth and fifth century Athens” (Matheson 1980, xii).

It wasn’t until the invention of glassblowing, which occurred between 27 BCE and 14 CE that glass started to become mass-produced (Bray 1995, 46). Blowing a glass vessel was much easier and quicker than casting or core-forming, and soon factories were built with tank furnaces to create blown vessels en masse. Requiring little ingenuity, mass-produced vessels often were blown into a mold to achieve the required shape. This produced uniform vessels quickly and cheaply. Artisans still used the original methods, but the time and labor that went into creating these “off hand working” objects increased their value significantly (Bray 1995, 46).

Scarcity of Evidence

...in any age of antiquity the ascertainable archaeological remains amount to no more than a minute fraction of what the civilisation in question actually produced, so it follows that when and where productive activity declines, surviving relics may grow so scarce as to give the impression of a total void. (Pallottino 1991, 98)

Now why is it, if metal objects were so important in the past that very few have shown up on the archaeological record? And if pottery was not as important, why do archaeologists find so much of it, specifically very fine examples in tombs? Some scholars have argued that since many tombs were found with a plethora of fine ware pottery and no metal objects, the people who created the tomb must have appreciated the pottery as the highest of art forms. It would seem that the opposite is in fact true. Metal objects were quite literally the source of one's wealth. Most of the time it would be rational to assume that a person would bequeath their wealth to a family member or friend upon their death, rather than having it buried with them; "we can see both Etruscan and Athenian elites using fine gold- and silverware in life, and passing it on to their heirs when they died, and the pots in their tombs used simply to provide the appearance of a respectable funeral without the expense" (Vickers & Gill 1996, 104). It is not to be said that burial rituals in the ancient Mediterranean were void of metal vessels. In fact, it may have been that metal vessels were placed on the funeral pyre for the service, but removed afterwards and reused. And since cremation was, at least in ancient Greece, reserved for the wealthiest elite, the tombs we discover might only show us the lower classes of the culture.

This argument does not hold true for the native Italian culture, the Etruscans. Some did practice cremation – we find many highly decorated cinerary urns in Etruria – but the upper class practiced inhumation. The surviving tombs are lavishly painted with bright frescoes of scenes of daily life and often designed to look like the interior of a house. Many goods were left in the tombs for the deceased, mainly of

ceramic. It has been estimated that nearly “90 per cent of the fine Athenian pottery in our museums” comes from Etruscan tombs (Vickers & Gill 1996, 72). One reason for their abundance is that, compared to precious metal objects, they were cost effective. “In antiquity, these pots will have provided the show, but not the expense, of an elaborate funeral. They will have served as ‘tokens and symbols’ substituted for the real wealth” (Vickers & Gill 1996, 72). Were it not for the Etruscans we might not have the substantial number of Greek fine ware pottery we do today.

Furthermore, from an early age technologies such as glass production were shrouded in secrecy and ritual. Workshops often passed down techniques from father to son or from master to apprentice. Metalworking was one of the first large-scale productions that spread through the ancient world, albeit quite slowly. In fact, it took three millennia for metallurgy to spread through the Middle East, from 7000 BCE to 4000 BCE. “This rate of ‘technology transfer’ is exceptionally slow... This reflects the secretiveness and conservatism associated with the ritual tied up with technology” (Henderson 2013a, 145-6). On the other hand, the “technology transfer” of glassmaking was incredibly quick, relatively speaking, spreading from Mesopotamia to Egypt in the sixteenth century with production flourishing until the eleventh century, and a resurgence in the late eighth century that continued throughout the Mediterranean. It was a slow rate of transfer to begin with, as only a small amount of beads and small objects were being made between the twenty-third and sixteenth centuries in northern Mesopotamia (Henderson 2013a, 145-6), but appeared rapidly in Egypt under Tuthmosis III to become a fully-fledged luxury craft production. Although we know glass production occurred on a large scale after its

resurgence in the eighth century, there is little to no evidence to show for it until the advent of glassblowing. “Even when glass objects were being produced in large quantities, such as in the late Hellenistic and early Roman periods, [evidence for *glassmaking*] can be difficult to find” (Henderson 2013a, 145-6).

Economy

The economy may have been a factor in the lack of artifacts: “Presumably during periods of relatively low ceramic imports of all kinds the social elite had chosen to acquire luxuries which do not register so conspicuously in the archaeological record. Metalware and glass for example, might have been more prevalent than table-ware pottery” (Fulford 1983, cited in Vickers & Gill 1996, 103). Contrarily, the example of ceramics missing from the archaeological record could be due to the poorer class not being able to afford it and the wealthier class using plate for vessels. The same could be said for glass. Before glass became affordable with the technology of glassblowing, it may have been too expensive for members of the lower classes and while affordable to the upper classes, plate vessels may have been preferred over glass. There are many reasons, both natural and cultural, why a material may be absent from the archaeological record. Unfortunately glass, and more importantly evidence for the production of glass, tends to be quite scarce.

Recycling

The reason so many of the metal artifacts that are supposed to have existed are nowhere to be found lies in the recyclability of the material. Unlike pottery, metal can be melted down and recast. Glass is recyclable, but the color of the glasses

is retained when melted and would mix. The disparity of amounts in written accounts and actual artifacts was nicely quoted by Lightbown, saying that metal artifacts, "like other forms of goldsmith's work, are always imperiled, even more than other works of art, by the intrinsic value of the precious metal, which has again and again brought destruction on them from a variety of causes" (1979, cited in Vickers & Gill 1996, 75). Glass can indeed be melted and recast, but metal was used as currency; its worth was in its weight, while the worth of glass objects would depend on its form. Glass is more fragile than metal, which could account for much of its absence in the archaeological record.

PART THREE - Scientific Analysis of Samples from Satricum

5. Scientific Analysis of Glass Technology

Categories of Glass Types

The formulae for glass production changed over time with the availability of materials and through the trade of ideas from one artisan to the next. The main types of glass in antiquity as denoted by Sayre and Smith are as follows (Henderson 2000, 50):

Type	Characteristic	Rough Dates
Soda-lime-silica	High magnesia (HMG)	c. 1500 – 800 BC
Soda-lime-silica	Low magnesia (LMG)	c. 800 BC – 1000 AD
Soda-lime-silica	High antimony	c. 600 – 200 BC
Islamic	High lead	c. 1000 – 1400 AD
Islamic	High magnesia	c. 840 – 1400 AD
Europe	Low magnesia, high potassium (LMHK)	c. 1150 – 700 BC
Chinese Han Dynasty	High potassium, high barium	c. 206 BC – 221 AD
India	High alumina	First millennium AD
Lead oxide-silica	High lead oxide	c. 10 th – 14 th century AD

While this does not encompass every type of glass ever made, it is a good approximation of the composition, time period, and rough location where these types were made. As expected from the timeframe, the analysis shows the Satricum samples fall into the low magnesia (LMG) category.

Lack of Evidence

Unfortunately, few sites have been found that can be unquestionably attributed to glassmaking. The discovery of an annealing oven within or beside a kiln could arguably point to the making or working of glass, however very few furnaces, regardless of the material they heated, have remained intact through the

centuries. Some kilns were dismantled to allow for the removal of the wares inside; if they were not to be used again there would be no point in reconstructing them once dismantled. Others have simply fallen into ruin over the passage of time. Most often the only remaining structure of a furnace is its foundation, which makes it quite difficult to discern its original configuration or use.

If a site is deemed to have held a furnace, it can then be problematic to determine what material the furnace was used for. Glassmaking and working required a furnace, but so did pottery and metalwork. Quite often it is almost impossible to determine what was being produced on a site. To further confuse the issue, a site with evidence of glass being worked could be a primary production site (where raw glass was made) or a secondary production site (where raw glass was remelted and worked into objects and vessels). Of course, a production site could make glass from raw materials straight into the final form of objects, but the plethora of raw glass pieces and ingots found throughout the ancient world indicates it is more likely that these two stages were separate and occurred in different locations.

To be completely sure that a furnace was used to make glass there needs to be evidence of glass in or around the furnace. Spills from a cracked crucible or dribbles from a sample being taken out of the glory hole could indicate glassmaking. However, other craft productions can also leave behind glassy slag residue such as metal smelting and faience production, so chemical analysis is required to conclusively deem the slag as glass. Scholars must make sure that it is indeed glass that is found at a site, “as distinct from glassy (fuel-ash) slags that can derive from

any high-temperature industry by alkali-rich fuel-ash combining with silica in bricks” (Henderson 2000, 40; Biek & Bayley 1979).

While there is an abundance of research on the history of glass, the morphology of vessel shapes, and the literary references in the historical record, very little has been proven about the provenance of primary production sites. Unfortunately for scholars, “...only in exceptional circumstances can analyses of glass be used to give a precise source of production” (Nicholson *et al.* 1997, 152). The ambiguity of the requirements for raw materials, i.e. sand, soda, and a flux, allowed for glass to be made throughout the ancient Mediterranean world.

Known Provenances

The chemical composition of the glass is unique to the specific furnace melt and will be a reflection of both the time and place where the glass was made. (Henderson 2013a, 319)

Very little is known about the primary production of glass in the Mediterranean. Much can be inferred from the remaining artifacts and parallels in the ceramic and metal industries, but there is still quite a bit to learn. While scholars know *how* glass was made in antiquity, there is little to no evidence as to *where* it was made. Between the eighth and first centuries BCE there is no evidence of glassmaking furnaces in Europe (Henderson 2013a, 94). Until glassmaking furnaces have been found and legitimized, scholars must rely on other clues to discern the provenance of an artifact.

For the Hellenistic Period, scholars have deduced that it is most likely that glass was produced in primary production sites in the Middle East and sent to secondary production sites closer to their distribution points (Aerts *et al.* 2003, 659-

60). Two large manufacturing centers were located in the Syro-Palestinian coastal region during the mid-second century BCE; examples of artifacts from this region have been found in Italy and Spain, among other areas of Europe (Grose 1989, 193). A study by Brems *et al.* determined six possible sources of sand throughout the Mediterranean, and other evidence has suggested primary production centers in Italy, Egypt, Cyprus, Rhodes, Macedonia, and other countries.

Just as with any other technology, the glassmaking process varied throughout time and between locations. Unfortunately for researchers, the composition of Hellenistic and Roman glass remained fairly unchanged for about 800 years (Aerts et al. 2003, 659), so compositional analysis can't always be completely relied on for provenancing an object. Definitively provenancing an artifact may not always be possible, but to get the closest approximation a combination of the location where the artifact was found, as well as the history of the culture, dating of the object (by carbon dating or any distinguishing traits), and typological, compositional, trace element, and isotope analyses must be examined together.

Isotopic Analysis

Elemental and isotopic analyses of ancient glass will reflect the compositional signature of the ingredients with which the glass was made, thus providing potential indicators for the production location of the glass. (Ganio et al. 2012a, 743)

Unfortunately for researchers, the three main components of glass are quite accessible throughout the ancient world. Sand can be found along any coastline, as well as desert areas and sometimes riverbanks, although it has been shown that

most sand is not preferable as a raw material for glass. Soda comes from plant ash or from natron collected from areas such as Wadi El Natrun. The stabilizer was often calcium oxide, which is found in limestone as well as an impurity in some sands in the form of shells. Small differences in impurities set different sources apart, but without specialized analyses it can be quite difficult to locate the source. The best way to determine the provenance of a piece of glass is to perform an isotopic analysis, specifically of the elements strontium and neodymium.

Due to their high masses and low relative mass differences, Sr and Nd isotopes are not measurably fractionated at the temperatures involved in glass melting, and therefore, their isotopic composition in a glass artifact will be identical to that in the raw materials from which it is derived. The Sr in glass is mainly incorporated with the lime-bearing constituents, being either shell or limestone, or lime-rich plant ash... Nd comes from the non-quartz or heavy mineral fraction of the silica raw material. (Ganio *et al.* 2012b, 1335)

The Sr-Nd isotopes can be used to provenance the original geological location of some of the raw materials, which could further illustrate the extent of trade in antiquity.

As the stabilizer is the third most prominent component and the first two are usually quite pure, calcium carbonate as lime is often analyzed for provenancing.

Lime is generally present in the range 5-10wt. %, and it is necessary to determine if it was added deliberately, as a third starting component, along with the silica and the soda. An indication of the form in which the lime was added can be gained through the investigation of the isotopes of the element strontium, which was typically added to the glass as a trace element present in calcium-rich minerals, especially in calcium carbonate. The strontium isotopes of seawater vary with geological time, a phenomenon which has been extensively studied in geochemistry, and the isotopic composition of sea water is inherited by the CaCO₃ that it precipitates, in the form of invertebrate shells and limestone. (Freestone 2004, 008.1.4)

Generic chemical analyses can be used to identify the types of raw materials used in the production of glass, but only isotopic and trace element analyses can truly

pinpoint an exact location. Isotopic analyses are critical to provenancing glass, as “they may show systematic variations around the Mediterranean Sea as a consequence of the differing geological environment” (Brems *et al.* 2012a, 120). Unfortunately for this study, “no clear distinctions in glass composition and origin between the different regions of the Roman Empire can be made based on the major elemental compositions” (Ganio *et al.* 2012a, 743) and only the analysis of the elemental compositions was available for this study.

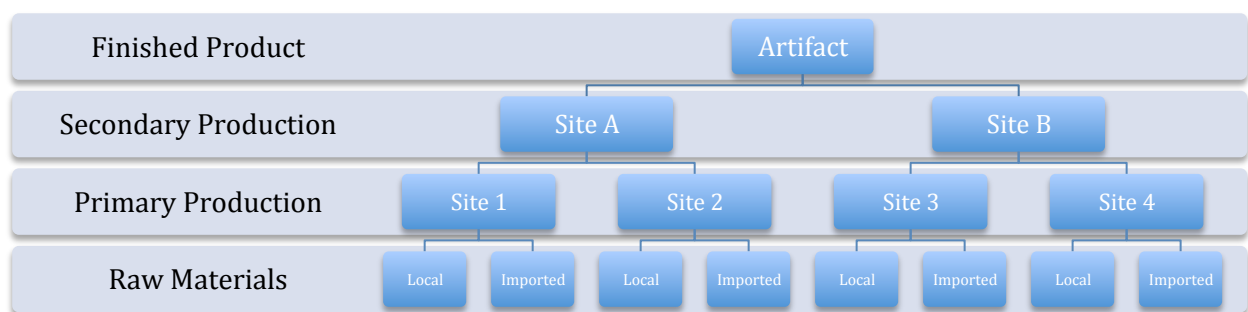
Issues

Finding the provenance of a piece of glass is further hindered by two main factors. First, scholars believe that most glass was *made* in one location and *worked* in another. A piece of glass may be worked in one area but traded and shipped to a completely different area, meaning that the resultant object may be of one culture’s form but another culture’s provenance. Would a Cyprus-made vessel made of Egyptian glass be considered Cypriot or Egyptian? It is widely believed that there may have been a few large primary workshops that supplied most of the glass in raw form for secondary workshops. The ingots found on the shipwreck at Ulu Burun provide early evidence for this theory. Second, glass was often recycled as cullet, meaning that glass from any number of origins could be melted down to create a new batch of glass. The isotopic analysis of the subsequent object then has the isotopic signatures of the previous pieces of glass. With a large trade network of raw glass throughout the Mediterranean, this can make determining an artifact’s origin troublesome. This issue is especially relevant if the model of a few primary workshops providing glass to many secondary workshops is true. Since there is no

concrete information on the exact production cycle of ancient glass, Freestone sums up the issues with provenancing artifacts based solely on composition:

...there were probably a small number of primary workshops making raw glass, and they appear to have been located near the sources of raw materials (sand and alkali) in Egypt and Palestine. Each primary workshop could supply a large number of secondary workshops with raw glass. Thus, many workshops could have been making vessels, windows or beads using glass made by a single primary source, and these would have been of essentially the same composition. On the other hand, a single workshop could, in principle, receive glass from more than one primary source, and thus would have produced vessels of two or more compositional types. (2004, 008.1.3)

The hierarchy chart below shows the many paths of production that could result in a final object.



Here is a theoretical example: Let's say a single artifact was created from the recycled glass of two vases, one from secondary production site A and one from site B. Site A used raw ingots it received from primary production sites 1 and 2, while site B used ingots from sites 3 and 4. Site 1 used imported materials, site 2 used local materials, site 3 used local materials, and site 4 used some local and some imported materials. For simplicity's sake let's say that the glass at the primary production sites was made using only calcium-rich sand and natron and the sand and natron were from separate locations. This then gives us eight locations (assuming none of the primary sites shared raw materials), five of which would be

local to the given primary production site, and three imported from elsewhere. Now include the chance for these raw materials to have impurities, the required addition of other materials to compensate for any instability from the impurities or the lack of a required element in the raw materials, the addition of excess silica from interaction with the furnace linings or crucibles, plus the addition of coloring agents that could happen at any point in the production. The possibilities are almost countless. Much more information about a given artifact or area is necessary before a provenance can be determined.

This alone shows the difficulties present in determining the provenance of a single artifact, but now take into consideration the fact that a votive deposit is usually the aggregation of objects from different people traveling from different origins. The samples analyzed from Satricum were found in a votive deposit, meaning each artifact could have a completely separate history from the others.

Ratios of Elements

When isotopic analysis is not available, there are other ways to infer the provenance of an artifact. Although the precise location of a source of raw material may not be known, comparisons of a set of artifacts can often show a pattern relating to origin. The amount of a given element, e.g. lime, in a set of artifacts can indicate if the raw materials that comprise them came from the same source. If there are identical, or near identical, amounts of various elements in different artifacts, it would be reasonable to believe the pieces came from the same workshop, if not the same batch. For example, “glasses made from the ‘Roman’ sand source contain a mean and standard deviation of $7.48 \pm 1.18\%$ calcium oxide (CaO), the glass from

the Wadi el Natrun lake was found to contain $3.44 \pm 1.68\%$ CaO and that from Taposiris $5.29 \pm 1.59\%$ " (Henderson 2013a, 247). While the location of the 'Roman' sand source mentioned there is unknown, it can be said that it is different than the sources of the glasses from Wadi el Natrun and Taposiris.

The levels of magnesium and potassium in a piece of glass are a very good way of quickly determining its flux. Between c. 800 BCE and 800 CE, natron was the main source of flux in the form of sodium bicarbonate. The Wadi el Natrun area contains alkaline lakes; evaporated lakebeds that contain deposits of natron. Before the eighth century BCE and after the eighth century CE, plant ash was used. Plant ash, also known as *potash*, is made by burning certain alkali-rich plants and washing the ashes. The plants used to create plant ash were halophytic plants, specifically of the genera *Salsola*, *Salicornia*, *Hammada*, and *Kali* of the subfamily *Salsoloideae* (Henderson 2013a, 31). These plants are often found in arid, desert locations, but seaweed has been suggested as an alternative. It is easy to distinguish between natron and plant ash glasses as glass made with plant ash will have higher potassium oxide and magnesium levels, since natron is deficient in potassium (Henderson 2013a, 98; Forbes 1966, 5:117-8).

Other ratios that are important in determining the provenance or time period of a piece of glass include the calcium oxide to magnesium ratio. Calcium was roughly in the range of 6.5% – 9% in glass through the first millennium CE (Henderson 2000, 28). If dolomitic limestone was used as the stabilizer, the calcium and magnesium oxide amounts would be nearly equal (Henderson 2013a, 65). The composition of dolomite is roughly 54.4% calcium carbonate and 45.6% magnesium

carbonate (Lucas 1934, 361). The calcium to magnesium ratio in dolomite is a positive correlation; near equal presence of both elements strongly indicates that dolomitic limestone was used. Egyptian glass was often made with dolomitic limestone, as proved by the CaO to MgO ratio. Unfortunately, the calcium levels could be altered. Before the first century BCE the interaction of the molten batch with the lining of the crucible that held it could raise the amount of alumina or calcium of the final product (Henderson 2013a, 94). So even if dolomitic limestone was used, the calcium and magnesium oxide amounts may not be equal.

Elements most often used to color a batch of glass include copper, cobalt, nickel, zinc, arsenic, and antimony. Although critical to the resultant color of a batch of glass, it is difficult to determine if the coloring was added to the raw materials or added subsequently during secondary production. Therefore, these elements are not nearly as helpful in determining the provenance of an object as the main elements, i.e. silica, sodium, calcium, potassium, alumina, iron, manganese, and magnesia (Aerts *et al.* 2003, 662).

Eutectic

As stated before, it is possible to make glass using just silica. It is also possible to make glass using just silica and sodium. This, however, produces a water-soluble glass, so calcium can be added as a stabilizer. These three elements, silica, sodium, and calcium, are the major components in most ancient glass. Known as *soda-lime-silica* glass, this was the most abundant type of glass in antiquity. The term *eutectic* is used in chemistry to denote “the one mixture of a set of substances able to dissolve in one another as liquids that, of all such mixtures, liquefies at the

lowest temperature” (Encyclopædia Britannica, “eutectic”). The addition of a flux to the silica reduces the melting point from 1710°C to a more manageable temperature. “The eutectic mixture [of glass] is one which has the lowest freezing point of all possible mixtures of sodium, calcium and silicon oxides” (Henderson 2000, 51). This eutectic mixture is comprised of 73.10% silica, 21.90% soda, and 5.00% calcium oxide and lowers the melting point to 725°C (Morey 1964, cited in Henderson 2000, 51). 725°C for this composition is the minimum liquidus temperature, meaning the “absolute melting temperature of the glass above which nuclei and crystals cannot form” (Henderson 2000, 51). Other combinations of these three elements result in “the liquidus temperature for a glass containing 18.8% Na₂O, 7% CaO and 74.2% SiO₂ is 867°C which rises to 1060°C for a glass having a composition of 17.6% Na₂O, 15% CaO and 67.4% SiO₂” (Morey 1964, cited in Henderson 1985, 272). The final combination is the closest to the Satricum samples, which consists of 67.32% SiO₂, 17.24% Na₂O, and 8.22% CaO. Of course, this ternary eutectic does not truly reflect glass in antiquity, as colorants, opacifiers, and impurities would have been present, meaning many more elements would be found in a set of results than just those three.

	SiO ₂ wt.%	Na ₂ O wt.%	CaO wt.%	Liquidus Temperature
Eutectic	73.1	21.9	5.0	725°C
Eutectic	74.2	18.8	7.0	867°C
Eutectic	67.4	17.6	15.0	1060°C
Satricum	67.32	17.24	8.22	
Prehistoric European soda-lime-silica	68 - 72	18 - 20	6 - 9	c. 1000°C – 1100°C

(Brill, cited in Henderson 1985, 272)

6. Scientific Methodology

The fragments analyzed were recorded as follows:

Sample Name	Vessel Shape	Body Color	Decoration	Fragment Color
SAT1 V528	Amphoriskoi	Cobalt blue body	Opaque yellow and white trails	Blue
SAT2 V2088	Oinochoi	(Pale) cobalt blue base	Trailed on opaque yellow	Blue
SAT3 V22718		Cobalt blue neck and shoulder	Trailed opaque yellow	Blue
SAT4 V2160	Alabastra	Cobalt blue neck		Blue
SAT5 V565		Cobalt blue shoulder	Trailed opaque yellow and white	Blue
SAT6 V730		Pale 'blue'	Combed opaque yellow	Blue
SAT7 V2331		Cobalt blue (largest of 2 fragments)	Trailed on opaque white, yellow, and turquoise, contains bubbles and inclusions	Blue
SAT8 V525		Cobalt blue wall, thick	Opaque white and thin opaque yellow	Blue
SAT 9 V10443		Rim and cobalt blue body	Opaque yellow and thin white	Blue
SAT10 V2537		Translucent blue (smaller piece)	Opaque white and yellow	Blue
SAT11 V759		Small cobalt blue vessel with everted rim		Blue

The eleven artifacts analyzed are all blue glass, mostly decorated with yellow- or white-combed trails. They vary in size up to 4 cm in length and were found in a temple votive deposit. They were discovered under the supervision of Professor Marijke Gnade from the University of Amsterdam, executive director of the Satricum Project since 1991. The Royal Dutch Institute at Rome started excavations at Satricum in 1977 and in 1990 the University of Amsterdam became the sole executor of the excavation. The fragments analyzed all date from the third to second centuries BCE and are classified as Middle Hellenistic, placing them in

Harden's Mediterranean Group 3 classification (or possibly Grose's Mediterranean Group 2).

The samples were analyzed by Electron Probe Microanalysis (EPMA) at the Open University by Dr. Andy Tindle. Electron microprobe analysis "involves the use of a micro-beam of electrons which are focused on the sample surface using electrostatic lenses. The electrons themselves are generated using an electron gun... The interaction of the electrons with the sample generates secondary X-rays which are characteristic of the chemical elements in the material" (Henderson 2000, 17; 2008, 6). A small sample approximately 1mm was pressure-flaked from the artifacts and mounted in a block of epoxy resin. These blocks were then polished flat with grinding diamond paste down to 0.5 micron. This removes any weathering and allows the "geometry of the analysis to be repeated exactly each time". Before analysis the resin blocks were coated in carbon to minimize distortion and make the surface conductive to electrons. The samples were analyzed with a Cameca SX100 electron microprobe using a defocused electron beam of 30 microns in diameter with a voltage of 20kV and a probe current of 15nA. National Institute of Standards and Technology (NIST) and Corning Museum of Glass standards for glass were analyzed regularly so as to check for instrumental drift.

7. Results

The results of the electron microprobe analysis and figures showing the correlations between elements are formatted horizontally in Appendix A and B.

The samples analyzed are from eleven separate objects (see Figures 3 and 4). Such a small sample set must be considered when reviewing the results. Due to the limited amount of results, the observations and conclusions stated herein are not in any way meant to be conclusive, but merely stating theories based on the resultant data.

Although there are a few discrepancies, the results from the eleven Satricum fragments are fairly homogeneous. The standard deviations of all the elements never exceeded 1.58 (this is the standard deviation for silica, with an average of 67.32%). The elements that showed the largest standard deviation (SD) were SiO, Na₂O, CaO, and Al₂O₃, in descending order of magnitude between 1.6 and 0.5. All the other elements had a SD below 0.3 (Figure 1). Fe₂O₃, PbO, and As₂O₅ had a SD between 0.30 and 0.22, and the SD of the rest of the elements fell below 0.16. The lower the SD, the more similar the results. Granted, a small SD relative to a small average can indicate a set of results over a large range. For example, Sb₂O₅ has an average of 0.040%, but the SD is 0.072. This gives a single SD range from 0.112% to -0.032%. Obviously a negative percentage here is impossible, meaning that although the SD is small in comparison to the SD of other elements, it is quite large relative to the average it relates to. The best way to get a smaller SD for a set of data is to exclude the outliers. Using the example of Sb₂O₅ again, when the outliers (SAT3 and SAT7 with percentages at 0.19% and 0.18% respectively) are removed from the set,

the new average is 0.008% (previously 0.040%) with a standard deviation of 0.014 (previously 0.072). Below are some of the results without the outliers and how they compare with the original data:

- Samples **SAT2** and **SAT5** have noticeably higher amounts of *silica* with 69.62% and 70.67% respectively
 - The average *silica* percentage without these two samples is 66.69%
 - The average of all samples for *silica* is 67.32%
 - The standard deviation for *silica* without these two samples is 0.79
 - The standard deviation of all samples for *silica* is 1.59
- Samples **SAT9** and **SAT10** have noticeably lower amounts of *silica* with 65.46% and 65.61% respectively
 - The average *silica* percentage without these two samples is 67.72%
 - The average of all samples for *silica* is 67.32%
 - The standard deviation for *silica* without these two samples is 1.47
 - The standard deviation of all samples for *silica* is 1.59
- Samples **SAT5** and **SAT11** have low *alumina* percentages at 1.30% and 0.99% respectively
 - The average *alumina* percentage without these two samples is 2.39%
 - The average of all samples for *alumina* is 2.17%
 - The standard deviation for *alumina* without these two samples is 0.17
 - The standard deviation of all samples for *alumina* is 0.53
- Samples **SAT3** and **SAT7** have high *lead* percentages at 0.50% and 0.66% respectively

- The average *lead* percentage without these two samples is 0.05%
 - The average of all samples for *lead* is 0.15%
- The standard deviation for *lead* without these two samples is 0.054
 - The standard deviation of all samples for *lead* is 0.22
- Samples **SAT3** and **SAT7** also have high *antimony* percentages at 0.19% and 0.18% respectively
 - The average *antimony* percentage without these two samples is 0.01%
 - The average of all samples for *antimony* is 0.04%
 - The standard deviation for *antimony* without these two samples is 0.014
 - The standard deviation of all samples for *antimony* is 0.07
- Samples **SAT2**, **SAT5**, and **SAT9** have low *calcium* percentages at 7.13%, 7.19%, and 6.85% respectively
 - The average *calcium* percentage without these three samples is 8.68%
 - The average of all samples for *calcium* is 8.22%
 - The standard deviation for *calcium* without these three samples is 0.15
 - The standard deviation of all samples for *calcium* is 0.77
- Sample **SAT11** has a very high *arsenic* percentage at 0.92%
- Samples **SAT1**, **SAT3**, **SAT6**, and **SAT9** have reasonably higher *arsenic* percentages at 0.58%, 0.46%, and 0.40% respectively
 - The average *arsenic* percentage without these five samples is 0.09%
 - The average of all samples for *arsenic* is 0.32%

- The standard deviation for *arsenic* without these five samples is 0.12
 - The standard deviation of all samples for *arsenic* is 0.29
- Samples **SAT2** and **SAT10** have low *iron* percentages at 0.63% and 0.31% respectively
 - The average *iron* percentage without these two samples is 0.99%
 - The average of all samples for *iron* is 0.89%
 - The standard deviation for *iron* without these two samples is 0.15
 - The standard deviation of all samples for *iron* is 0.26
- Samples **SAT1** and **SAT4** have high *iron* percentages at 1.32% and 1.10% respectively
 - The average *iron* percentage without these two samples is 0.82%
 - The average of all samples for *iron* is 0.89%
 - The standard deviation for *iron* without these two samples is 0.23
 - The standard deviation of all samples for *iron* is 0.26
- Samples **SAT5** and **SAT6** have high *manganese* percentages at 0.41% and 0.40% respectively
 - The average *manganese* percentage without these two samples is 0.17%
 - The average of all samples for *manganese* is 0.21%
 - The standard deviation for *manganese* without these two samples is 0.078
 - The standard deviation of all samples for *manganese* is 0.12

Relative outliers include:

Sample	High Levels	Low levels
SAT1 BI	Iron, arsenic	-
SAT2 BH	Silica	Iron
SAT3 BF	Lead, arsenic, antimony	-
SAT4 BE	Iron, silver	-
SAT5 BD	Silica, manganese	Potassium
SAT6 BC	Manganese	-
SAT7 BB	Lead, antimony	-
SAT8 BA	-	Arsenic
SAT9 BL	Sulfur, silver	-
SAT10 BK	Chlorine, magnesium, barium	Manganese, iron, copper, cobalt, arsenic
SAT11 BJ	Arsenic, silica	-

Note: SAT3 and SAT7 were distinct enough from the other samples to warrant mention. In the compilation of figures any circle that is shaded green indicates the two contained points are SAT3 and SAT7.

Silica

Silica is the major component of glass. Samples SAT2, SAT5, and SAT11 have slightly higher silica content than the rest of the samples. To determine what type of material was used to provide the silica we look to the alumina and calcium oxide contents, as they could indicate possible impurities such as feldspar, calcite, sphenes, or clay: “the relatively high alumina content (almost always very near 2.5 wt.%) and higher calcium oxide values (6–9%) exclude a pure silica source such as

chert... Thus it seems that the source of silica for Roman glass was a clean sand of very high quartz content” (Aerts *et al.* 2003, 663-4). The results from Satricum agree with this statement (Figure 10), indicating that a clean sand source was most likely the source of silica for the analyzed fragments, although because of the differences in aluminum content, SAT 5 and 11 almost definitely came from a different sand source than the others.

Calcium and Aluminum

SAT2, SAT5, and SAT9 have significantly lower levels of calcium oxide than the rest of the samples. The differences in the two groups (higher and lower calcium oxide levels) could indicate separate batches with different calcium sources. A use of different calcium sources in the raw materials could indicate different primary production sites (Henderson 2013a, 243). When plotting the calcium and alumina wt.% against each other, there seem to be four separate groups (Figure 10). SAT11 has low alumina, high calcium; SAT5 has low alumina, low calcium; SAT2 and SAT9 have high alumina, low calcium; the rest of the samples have high alumina, high calcium.

Cobalt and Copper

All the samples analyzed were of blue colored glass. It would be logical then to find either small amounts of cobalt, copper, or iron as the colorant. Cobalt was the most common element used in dark blue glass; alternatively “copper of the order of 1 per cent or less produces a paler blue even in a 2-5 percent lead enamel, whilst 2 per cent or more of copper makes a green vitreous material, at least when this also

contains larger amounts of lead (4-35 percent)” (Biek & Bayley 1979, 8). The largest amount of copper in the samples is 0.38% (from SAT3 BF) and is on average 0.20%, which is not enough to make the dark blue color of the samples. Cobalt is usually found in much smaller quantities in glass; even for deep blue glass there is often less than 2% cobalt oxide and can be as low as 0.05% (Biek & Bayley 1979, 8; Henderson 2000, 29). With an average of 0.12% cobalt oxide it can be said with relative certainty that for the majority of the samples cobalt was used as the main colorant.

Curiously, SAT10 measured 0.00% for cobalt and only 0.01% for copper. Cobalt and copper are the two main colorants used to create blue glass, and the absence of both is puzzling (Figure 20). Iron, which in its reduced state can produce a green hue, is only at 0.31%. This is the lowest amount of these three elements for all the samples. SAT2 also has quite low amounts of cobalt, copper, and iron, but not as dramatically different as SAT10. This possibly can be explained by the fact that SAT10 is specifically categorized as “translucent blue” and SAT2 as “pale blue”. SAT6 also shows low amounts of cobalt with 0.08% and is also described as “pale ‘blue’”, but SAT11, which has the same wt.% of cobalt as SAT6, is characterized as “cobalt blue”. Only 0.05% of cobalt oxide is necessary to provide a strong blue color, but relative to the other pieces SAT2 and SAT6 have lower than average wt.%, which could account for their paleness.

Cobalt is often found in ores along with iron, nickel, zinc, and arsenic. Comparing these elements can sometimes indicate which type of ore was used as the colorant (Shortland and Schroeder 2009, 958). Figures 27 and 28 show the correlation of iron and arsenic to cobalt and zinc and nickel to cobalt, respectively.

Cobalt has a positive correlation with iron, arsenic, and nickel, but a negative correlation with zinc.

Figures 25 and 26 show the correlation of iron and arsenic to copper and zinc and nickel to copper, respectively. Copper and iron had a positive correlation, while copper and the other three elements had a slight negative correlation. Figure 16 shows the positive correlation between copper and lead, indicating that the copper may have been added to the batch as a copper-based alloy that was softened by lead (Aerts *et al.* 2000, 117).

Antimony and Lead

The higher than average levels of lead and antimony in SAT3 and SAT7 could indicate the presence of bindheimite $Pb_2(Sb,Bi)_2O_6$ or lead pyroantimonate $Pb_2Sb_2O_7$, both used in opaque yellow glasses (Fleming 1999, appendix A 140-4). Although all the samples utilized blue fragments, it is possible that some yellow opaque decoration on these two samples contaminated the fragment. That, however, is unlikely. The correlation between antimony and lead seems to be 1 : 3 (see Figure 6) and the levels of both elements are not high enough to indicate contamination. “As well as a reduction in the glass’s melting point, lead increases the solubility of antimony, tin and copper oxides at high temperatures, leading to glass opacification if crystals precipitate out at lower temperatures” (Henderson 1985, 276). Given the correlation between lead and antimony and lead and copper, the high amount of lead in SAT3 and SAT7 is most likely responsible for the high amount of antimony and copper. Antimony was often added to a batch as “stibina, a Sb-S mineral, [or as]

a Sb-Pb mineral or alloy, of which the latter seemed to have been used more often” (Aerts *et al.* 2000, 119). SAT4, SAT5, and SAT8 may have used stibina in their batch (Figures 6 and 15).

The combination of antimony and copper creates an opaque turquoise color (Figures 13 and 14). Samples SAT1, SAT2, SAT6, SAT9, SAT10, and SAT11 have no antimony and various amounts of copper, but samples SAT3, SAT4, SAT5, SAT7, and SAT8 show a positive correlation of $y = 1.2x + 0.15$ with x being the wt.% of antimony and y being the wt.% of copper. Antimony can sometimes be found as a small impurity in copper (Lucas 1934, 152).

Iron

Iron is most often introduced to a batch of glass as impurities in the sand source. Impurities include iron oxides, iron titanates, or silicates, specifically magnetite, ilmenite, or zircon. Unfortunately, iron is not very helpful to use in determining provenance as it “can occur in different minerals in the sands, silicates or oxides and thus enter into the glass compositions in different forms and at different stages of its elaboration” (Aerts *et al.* 2003, 664). Figures 11, 17, 25, and 27 show the wt.% of iron against alumina, manganese, copper, and cobalt, respectively.

Alkalis

The amount of alkalis can help specify the modifier used in a batch, since glass made with plant ash will have higher potassium oxide and magnesium levels than glass made with natron. This is because natron is deficient in potassium (Henderson 2013a, 98; Forbes 1966, 5:117-8). The potassium oxide to sodium oxide

ratio (Figure 22) and magnesia to potassium oxide ratio (Figure 9) can also indicate which type of flux was used, as “even in Roman glasses where potash might have been added to natron we seldom find more than 2 percent of K_2O ” (Forbes 1966, 5:117-8).

Correlations

The correlation between sulfur and antimony may be 1 : 2 for SAT3 and SAT7, while the rest of the samples have little to no antimony regardless of the amount of sulfur (Figure 15).

The correlation between copper and lead seems to be 1 : 1.5 (Figure 16).

The correlation between zinc and copper seems to be negatively 1 : 10 (Figure 26).

Iron and aluminum do not seem to be correlated in any way, with the majority of the aluminum percentages between 2.12% and 2.62%, regardless of the amount of iron. SAT5 and SAT11 are outliers with 1.30% and 0.99% of aluminum respectively (Figure 11).

For aluminum versus calcium the data seems to be split into four ‘quadrants’. There are high and low aluminum results and high and low calcium results. One result came back for low-aluminum-low-calcium (SAT5) and low-aluminum-high-calcium (SAT11) each, two results had high-aluminum-low-calcium (SAT2 and SAT9), and the seven other fragments had high-aluminum-high-calcium (Figure 10).

Lead and sodium do not seem to have a correlation, as nine of the fragments have 0.16% or less of lead, regardless of the amount of sodium. This is excluding the two outliers, SAT3 and SAT7, with 0.50% and 0.66% respectively (Figure 12).

Eutectic

The average percentages of the Satricum samples as compared to the ternary eutectic show lower silica and soda levels, but higher calcium oxide levels (Figure 2). The eutectic is 5.81 percentage points higher than the Satricum samples for silica, 4.72 points higher for soda, and 3.24 points lower for calcium oxide. As compared to the 73.10% SiO₂, 21.90% Na₂O, and 5.00% CaO for the eutectic, the averages of the samples analyzed were 67.29% SiO₂, 17.18% Na₂O, 8.24% CaO, with 7.29% as other elements.

<i>Element</i>	<i>Eutectic Percentages</i>	<i>Average Satricum Percentages</i>	<i>Difference in Percentages</i>
<i>SiO₂</i>	73.10	67.29	5.81
<i>Na₂O</i>	21.90	17.18	4.72
<i>CaO</i>	5.00	8.24	-3.24
<i>Other</i>	0	7.29	-7.29

The analyzed samples from Satricum fit into Henderson’s category of “Roman sand source” (2013a, 247) and possibly either Harden’s Mediterranean Group 3 category or Grose’s Mediterranean Group 2.

Soda–lime–silica glasses are characterized by “low levels of potash and magnesia (< 1.5 wt.%)” as well as “significant amounts of alumina (generally near 2.5%) and calcium oxide (between 6 and 8%)” for the period between the ninth

centuries BCE and CE (Shortland and Schroeder 2009, 954). The Satricum samples agree with these criteria, with 0.47% potassium, 0.55% magnesia, 2.17% alumina, and 8.24% calcium oxide.

Contemporary or Similar Data

Beirut

Of the few glassmaking furnaces that have been found, one of the most important is located in Beirut. The tank furnaces discovered at Beirut are nearly six meters long, indicating that glass was produced on a large scale there. The site was located next to the Roman colony of Julia Augusta Felix and dates to before 50 CE with evidence putting the first complex before 50 BCE (Henderson 2013a, 215-6). It is very significant, as it is “the only definitive evidence, on this scale, for primary glassmaking that includes the evidence of glass-melting furnaces for the late Hellenistic – early Roman period from the Levant” (Henderson 2013a, 222).

The furnaces at Beirut are of particular relevance to the analysis of the samples in this paper as they also date to the late Hellenistic-early Roman period. The data from Beirut can “provide a benchmark against which to compare contemporary raw and vessel glasses found in Beirut and elsewhere” (Henderson 2013a, 242-3). Furthermore, although there is no evidence yet to prove that glass vessels were produced in Italy during this time period, scholars are confident that they were. While the provenance of a suspected Italian-made vessel may not be available, the analysis of its composition can be compared to the raw glass from

Beirut to “provide provenance information, or at least provide supporting evidence that they were not made in Beirut” (Henderson 2013a, 242-3).

Qumrân

A study by Aerts *et al.* analyzed ninety glass fragments from the site of Khirbet Qumrân in Israel dating from c. 4 BCE – 68 CE (2000, 114). Of the ninety, fifty-nine fragments were able to be divided into different typological groups using a “descriptive index [that] was worked out in which each specimen was described individually by eighteen properties covering the form, the dimensions, the fabrication technique, the condition of conservation and the restoration treatment” (Aerts *et al.* 2000, 114). Once analyzed, using electron probe X-ray microanalysis (EPXMA), the fifty-nine fragments were subdivided into three groups based on their results.

Unfortunately, the glass fragments from Qumrân date a few centuries after the samples from Satricum, and are of natural blue-green color rather than dark blue. Still, the parallels in results, specifically between the Satricum samples and the Qumrân Group 3 samples, show the amount of consistency in glassmaking from the Hellenistic through Roman periods.

Nimrud, Eli’ezer, Dor, London, Beirut, Al-Raqqa, Torcello, Mai’e Pur

Henderson (2013a, 91-7) presents a set of results from eight different sites from eight very different dates between the ninth century BCE and the twelfth century CE. The results indicate that the Satricum samples correlate with the data from Beirut, which is promising as the samples from Beirut have the closest time

span to the Satricum fragments. Figures 29 and 30 show the data from these eight sites. Nimrud, London, and Torcello appear to have been made with plant ash, as their magnesium and potassium levels are higher than the others. Oddly, the London samples date from the first century CE, during the middle of the time period that utilized a natron-based flux, appear to have used plant ash or mixed alkalis, however this may be explained by its location. The distance from natron sources may have made it necessary to alter the recipe. Plant ash would have been far more accessible than natron at the time. Eli'ezer, al-Raqqa, and Mai'e Pur were most likely natron-based samples, while Dor may have been a mixed alkali glass. Beirut has similar magnesium amounts as Eli'ezer, al-Raqqa, and Mai'e Pur, but slightly higher potassium levels. Historically it is more likely that samples from Beirut would have used natron, but these samples may have used a mixed alkali source.

Etruscan

The Etruscans were quite skilled in the ceramic and metalworking technologies, so it stands to reason that they may have also produced glass. Towle and Henderson analyzed eighteen samples from possible Etruscan glass artifacts dating circa 800-500 BCE (2007, 51). Although there is no proof so far that the Etruscans did make glass, this is most likely due to the lack of evidence apparent in many fields of ancient glass research. The eighteen samples are deemed to be most likely of Etruscan origin "on the basis of their distinct decoration and limited distribution. On this basis, there is a suggestion that glass working rather than glass-making may have occurred [in Etruria]" (Towle & Henderson 2007, 50). This

concur with the theory that primary production sites were located in the Middle East and the secondary production sites were located throughout the Mediterranean.

Three groups were categorized based on their analyses: high potassium glass, high magnesium soda-lime-silica glass, and low potassium soda-lime-silica glass. The second category indicates plant ash was used as a flux while the third group indicates natron. The twelve samples in the third group correspond with the composition of the Satricum samples, and only three were colored blue. As seen in Figure 31 the averages of the three blue Etruscan samples are compared to the samples from Satricum and data from Qumran and Beirut. Due to the very high level of copper these samples are most likely of a slightly lighter blue than the Satricum samples, as copper is a weaker colorant than cobalt. Although the analyses are not completely congruous with the samples from Satricum, the fact that other evidence suggests an Etruscan glass working industry provides Etruria as another viable option of provenance.

Possible Sand Sources

Analyses carried out on sand from the River Belus showed it contained 81.3% SiO₂, 4.26% Al₂O₃, 0.13% Fe₂O₃, 8.81% CaO (Turner 1954, cited in Henderson 1985, 271). While obviously not a perfect match given that these results are of the raw material while the final results are of fused glass, the River Belus was a popular sand source, and theoretically could be the one utilized in the Satricum fragments.

A comprehensive study by Brems *et al.* analyzed 178 different sand sources from across the Mediterranean. Most of the sources were incompatible for glassmaking with too low levels of silica, too much alumina or iron oxide, and either too much or too little calcium oxide. Only six sources were determined to be able to “produce a glass with major and minor elemental compositions within the ranges of Roman imperial natron glass” (Brems *et al.* 2012b, 2897). These six sites are “in the Basilicata and Puglia regions (SE Italy), and Tuscany (W Italy),... the Huelva province (SW Spain), the Murcia region (SE Spain) and from the Provence (SE France) [region]” (Brems *et al.* 2012b, 2905-6). While the River Belus may be an option for the sand source of the Satricum glass objects, Tuscany also provides a viable option and is located much closer to Satricum. However, proximity to a source does not necessarily dictate a sample’s provenance due to the extensive glass trade network of the time period.

8. Conclusions

...only in exceptional circumstances can analyses of glass be used to give a precise source of production. (Nicholson et al. 1997, 152)

[Unfortunately, this is not one of those times]

When working with such a small data set, it can be difficult to attain conclusive findings. Small differences in the results could be irrelevant, or could indicate completely different provenances. For the most part, samples SAT3 and SAT7 are very similar and slightly distinct from the other samples. This could indicate that they came from a separate batch of glass. Due to their similarities they very well could both come from the same batch of raw glass, although their differences in arsenic do set them apart from each other. Although the samples all vary slightly in their constituents, none are strikingly different enough to suggest a completely different provenance.

Due to the lack of discovered contemporary furnaces, it is impossible at the moment to pinpoint where these glass samples were made. However, there are some areas that are logical options. Evidence supports the theory that the areas of primary production in the early Hellenistic Age may have been in Italy or Macedonia, while in the late-Hellenistic period (c. second to first century BCE) the most likely location is in the Syro-Palestinian area, with other possible locations at Alexandria, Italy, and Rhodes (Henderson 2013a, 210). These eastern Mediterranean sites, specifically of the Syro-Palestinian area, have a long history in the glass industry, so while it cannot yet be proven, it is logical that the fragments

from Satricum may have originated from one of these areas in the centuries prior to their prime.

Generic chemical analyses can be used to identify the types of raw materials used in the production of glass, but only isotopic and trace element analyses can truly pinpoint an exact location. Again, “no clear distinctions in glass composition and origin between the different regions of the Roman Empire can be made based on the major elemental compositions” (Ganio *et al.* 2012a, 743). Unfortunately, isotopic analysis was not available for this study, so there can be no solid conclusions on the provenance. However, based on the results of the Satricum samples analysis, a few inferences can be made.

Dating in the third to second centuries BCE it should be assumed that natron rather than plant ash was used as the flux for these samples. Glass made from natron has much lower potassium and magnesium contents than plant ash glasses. “[E]ven in Roman glasses where potash might have been added to natron we seldom find more than 2 percent of K_2O ” (Forbes 1966, 5:117-8). With a potassium wt.% of 0.47 and given the time period, it can be said with definite certainty that the samples from Satricum were made with natron.

Soda–lime–silica glasses are characterized by 2.5% alumina, 6 – 9% calcium oxide, and less than 1.5% magnesia and potassium, which is consistent with glass samples from the Mediterranean from the ninth century BCE to the ninth century CE (Shortland and Schroeder 2009, 954; Aerts *et al.* 2003, 663-4; Henderson 2000, 28). The Satricum samples agree with these criteria, containing 2.17% alumina, 8.24% calcium oxide, 0.47% potassium, and 0.55% magnesia. These amounts of alumina

and calcium oxide also indicate a clean sand source rather than a pure silica source (i.e. quartz pebbles or chert) for the samples from Satricum. “[G]lasses made from the ‘Roman’ sand source contain a mean and standard deviation of $7.48 \pm 1.18\%$ calcium oxide (CaO)” (Henderson 2013a, 247). With a mean wt.% of 8.24 and a standard deviation of 0.774, the Satricum samples fit both parameters.

One possible option of a sand source could be the River Belus. The analyzed sand contained 81.3% SiO₂, 4.26% Al₂O₃, 0.13% Fe₂O₃, 8.81% CaO (Turner 1954, cited in Henderson 1985, 271), which is close to the Satricum results of 67.29% SiO₂, 2.17% Al₂O₃, 0.88% Fe₂O₃, and 8.24% CaO. The discrepancies are due to the fact that the River Belus sand was analyzed as raw sand while the Satricum samples are fused glass, but since it was a popular sand source, it should not be ruled out as a possible source of the raw sand used in the production of the Satricum samples. Isotopic analyses has also suggested that primary workshops may have been located in the western part of the Roman Empire during the Hellenistic and Roman eras (Brems *et al.* 2012a). It is possible that a closer source, possibly in Tuscany, could be the origin of the sand used to make the glass. Further research must be done to narrow down the possibilities of silica provenance.

Since all the samples are of a blue color, it stands to reason that the batches were either colored with cobalt, copper, or iron. Cobalt would be the most likely colorant, especially since less than 2% is needed to give a batch a strong color, with a minimum of 0.05% (Henderson 2000, 29). With a mean of 0.12% this is enough to have colored the batches. Copper is also present in the samples, with the largest amount of copper being 0.38% (from SAT3) and having an average of 0.20%. The

positive correlation between copper and lead could indicate that the copper may have been added to the batch as a copper-based alloy that was softened by lead (Aerts *et al.* 2000, 117).

It is most likely that the glass was produced in one area and traded to another area, as this is the current theory scholars have of the glass production industry. If this is the case then the secondary workshop may have mixed raw glass from multiple primary workshops, confusing the characteristics of the original sources. The glass may also be of recycled glass objects or cullet, also confusing the sources.

Issues

Here are some of the main issues present in attempting to provenance ancient Mediterranean glass objects:

- No literary sources before the Medieval Period
- No physical evidence of glassmaking kilns in Europe for a seven hundred year period (eighth to first centuries BCE)
- Possibility of recycling glass from different sources to make new objects
- Possibility of using ingots from multiple primary production sites in secondary production
- Impurities from various sources can alter color and obscure primary source locations
- Color could have been added to the batch after the main raw materials were mixed, changing the chemical composition of the batch

- Glass production was an oral tradition and would have been based on trial and error over the millennia
- The batch of glass may not have been fully mixed
- Different colored decoration could have contaminated an analyzed sample
- Human error in analyzing the samples
- Artifacts found in a votive deposit could have any number of origin locations

Final Thoughts

Based on the limited information of these samples and current research on glass provenancing, it is reasonable to guess that the glass may have been created in a primary production center in or near the Levant and worked at a secondary production center in Italy. However, it cannot be said with absolute certainty at this time whether the objects the samples came from were even from the same secondary workshop. Being a temple site, Satricum would have drawn multitudes of people to the shrine of Mater Matuta. Customarily, votive offerings would be left by the pilgrims in honor of the goddess. Coins, statues, food, and inscriptions were popular along with glass objects. It is very well possible that each of the eleven samples came from eleven separate objects brought by eleven separate pilgrims from eleven separate workshops! Without the help of isotope analysis and since there are no unique characteristics of the physical appearance of the samples there unfortunately cannot be a definite provenance for any of the artifacts at this time. The only conclusive statements that can be made agree with the scholarly definitions: these samples match the Roman glass criteria and were made using

natron rather than plant ash. However this is already assumed of the samples given their location.

Given all these conclusions from the results and the information available regarding Hellenistic glass and the site of Satricum, the most logical supposition of the provenance of the Satricum samples is extremely vague. While it can be inferred that the silica source was clean sand, the rest of the analyses fall into the main category of “Roman glass.” The River Belus is an option for the sand source, since it’s composition is similar to the samples and was a popular source during the time period, but it cannot be said with certainty that it was the source of silica for these objects.

If the samples analyzed for this paper were from a single set of objects from a less fluid site (for example, tableware from a villa) the provenancing would be simpler to deduce. The samples might have similar data, which could indicate they came from a single set of objects, probably from the same manufacturer. This could then be narrowed down to determine where the objects may have been bought, given the location of the site, which could then be extrapolated to where the objects may have been made. Using information on trade routes in the area and possible locations of raw materials, cross-referenced with the analyzed data, a provenance for the object and its raw materials could be suggested. However with the samples analyzed in this paper there are far too many variables to conclusively suggest a single provenance for any of the artifacts.

Appendix A - Results

The results of the electron microprobe analysis are formatted horizontally on the following pages.

Table 1

<i>Sample</i>	<i>SiO₂</i>	<i>Na₂O</i>	<i>CaO</i>	<i>Al₂O₃</i>	<i>P₂O₅</i>	<i>SO₃</i>	<i>Cl</i>	<i>K₂O</i>	<i>MgO</i>	<i>MnO</i>	<i>Fe₂O₃</i>	<i>CuO</i>	<i>Sb₂O₅</i>
SAT1 BI	66.63	16.15	8.87	2.44	0.10	0.23	1.29	0.42	0.55	0.16	1.20	0.24	0.08
SAT2 BH	69.62	16.55	7.13	2.47	0.01	0.25	1.01	0.49	0.42	0.31	0.63	0.10	0.00
SAT3 BF	66.62	17.38	8.39	2.12	0.07	0.36	1.04	0.61	0.62	0.13	0.99	0.38	0.19
SAT4 BE	66.40	16.77	8.81	2.45	0.05	0.18	1.20	0.42	0.63	0.18	1.10	0.23	0.04
SAT5 BD	70.67	16.58	7.19	1.30	0.06	0.21	1.22	0.32	0.56	0.40	0.86	0.14	0.01
SAT6 BC	67.27	17.39	8.53	2.62	0.08	0.26	1.09	0.39	0.41	0.41	0.80	0.21	0.00
SAT7 BB	66.91	17.62	8.60	2.15	0.05	0.37	1.00	0.61	0.61	0.16	0.97	0.35	0.18
SAT8 BA	67.12	17.84	8.73	2.44	0.02	0.20	1.33	0.44	0.64	0.14	0.91	0.17	0.03
SAT9 BL	65.46	17.87	6.85	2.49	0.09	0.46	0.96	0.50	0.45	0.19	0.91	0.26	0.00
SAT10 BK	65.61	18.94	8.85	2.36	0.06	0.20	1.43	0.50	0.71	0.02	0.31	0.01	0.00
SAT11 BJ	67.94	15.85	8.65	0.99	0.01	0.29	1.05	0.50	0.48	0.23	1.02	0.13	0.00
Average (wt.%)	67.29	17.18	8.24	2.17	0.05	0.27	1.15	0.47	0.55	0.21	0.88	0.20	0.05
Standard Deviation	1.590	0.896	0.774	0.530	0.032	0.088	0.153	0.088	0.099	0.119	0.243	0.107	0.072

<i>Sample</i>	<i>TiO₂</i>	<i>BaO</i>	<i>SnO₂</i>	<i>CoO</i>	<i>ZnO</i>	<i>PbO</i>	<i>Cr₂O₃</i>	<i>As₂O₅</i>	<i>NiO</i>	<i>V₂O₅</i>	<i>Ag₂O</i>	<i>Total</i>
SAT1 BI	0.05	0.02	0.02	0.24	0.02	0.05	0.01	0.00	0.00	0.00	0.02	98.77
SAT2 BH	0.05	0.06	0.00	0.04	0.03	0.01	0.00	0.23	0.00	0.03	0.00	99.44
SAT3 BF	0.16	0.01	0.05	0.13	0.01	0.50	0.00	0.58	0.01	0.01	0.00	100.34
SAT4 BE	0.02	0.05	0.00	0.16	0.01	0.16	0.02	0.25	0.02	0.02	0.01	99.16
SAT5 BD	0.12	0.09	0.04	0.17	0.00	0.00	0.00	0.17	0.02	0.00	0.00	100.10
SAT6 BC	0.06	0.01	0.01	0.08	0.02	0.10	0.01	0.46	0.01	0.00	0.00	100.20
SAT7 BB	0.12	0.03	0.00	0.11	0.01	0.66	0.00	0.00	0.00	0.04	0.00	100.53
SAT8 BA	0.09	0.00	0.00	0.14	0.01	0.08	0.00	0.00	0.00	0.00	0.00	100.31
SAT9 BL	0.04	0.03	0.00	0.20	0.01	0.00	0.02	0.40	0.00	0.06	0.01	97.27
SAT10 BK	0.04	0.12	0.05	0.00	0.05	0.01	0.00	0.00	0.02	0.03	0.00	99.30
SAT11 BJ	0.10	0.00	0.00	0.08	0.02	0.04	0.00	0.92	0.00	0.00	0.00	98.31
Average (wt.%)	0.08	0.04	0.01	0.12	0.02	0.15	0.01	0.27	0.01	0.02	0.00	99.43
Standard Deviation	0.044	0.038	0.021	0.070	0.014	0.223	0.009	0.296	0.009	0.019	0.007	1.015

Figure 1

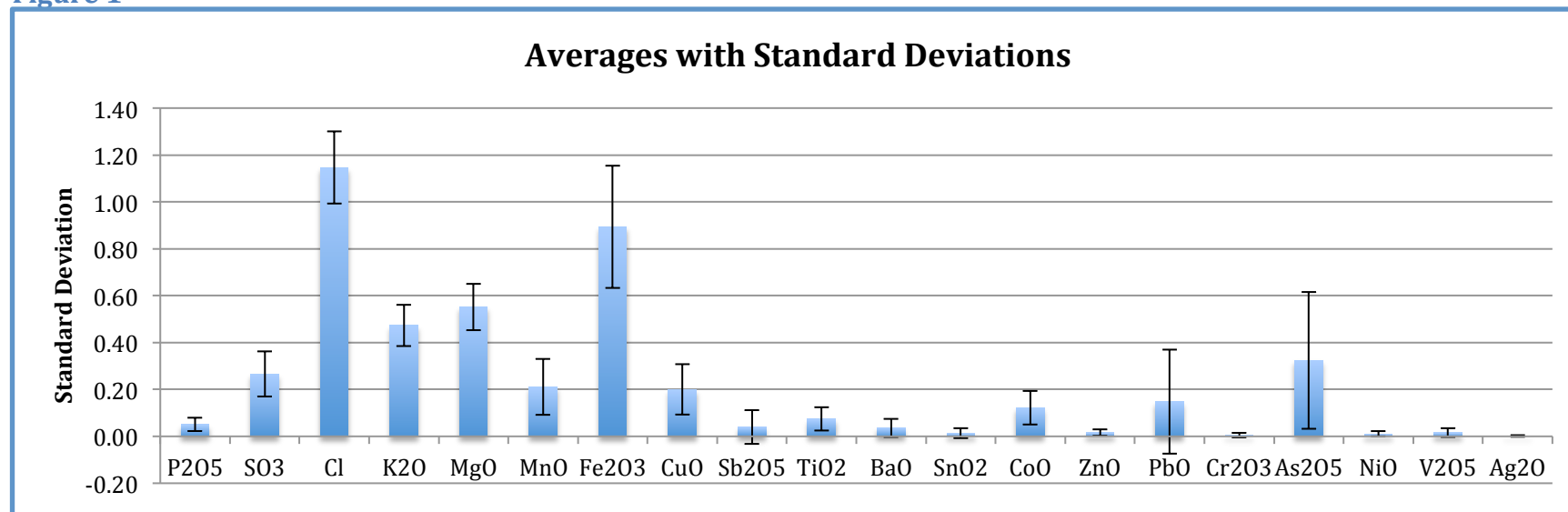


Figure 2

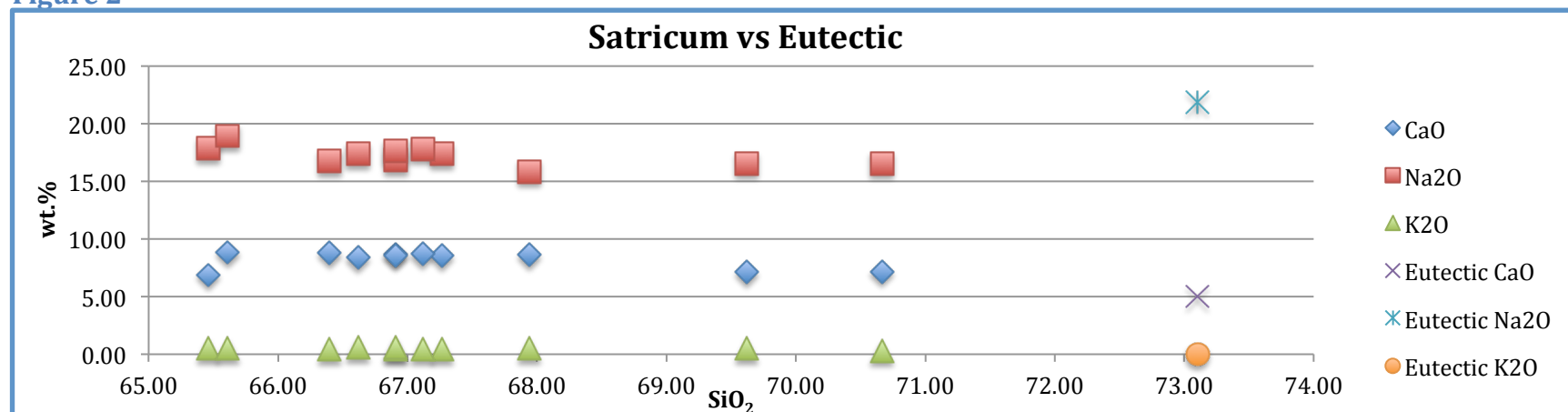


Figure 3

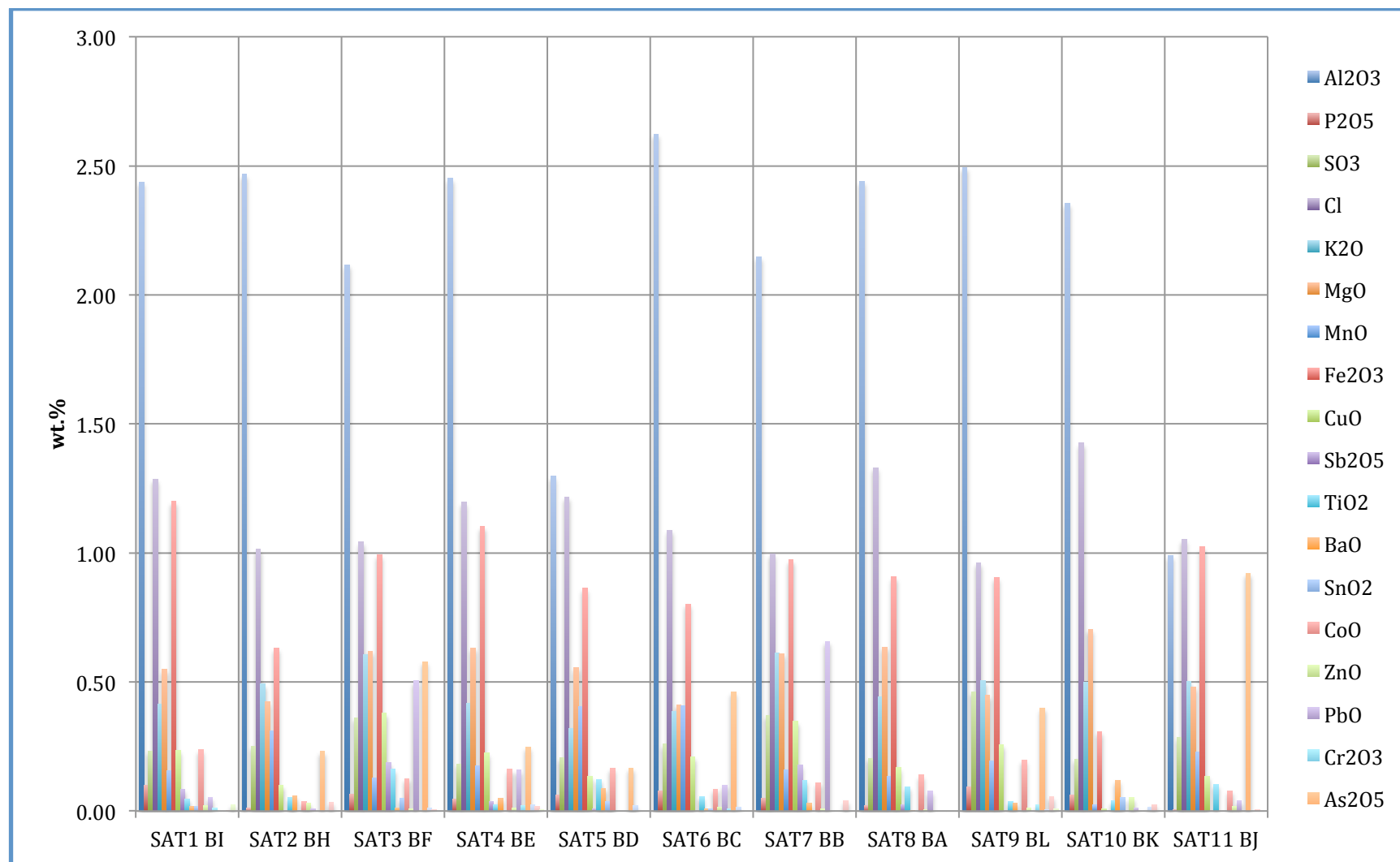
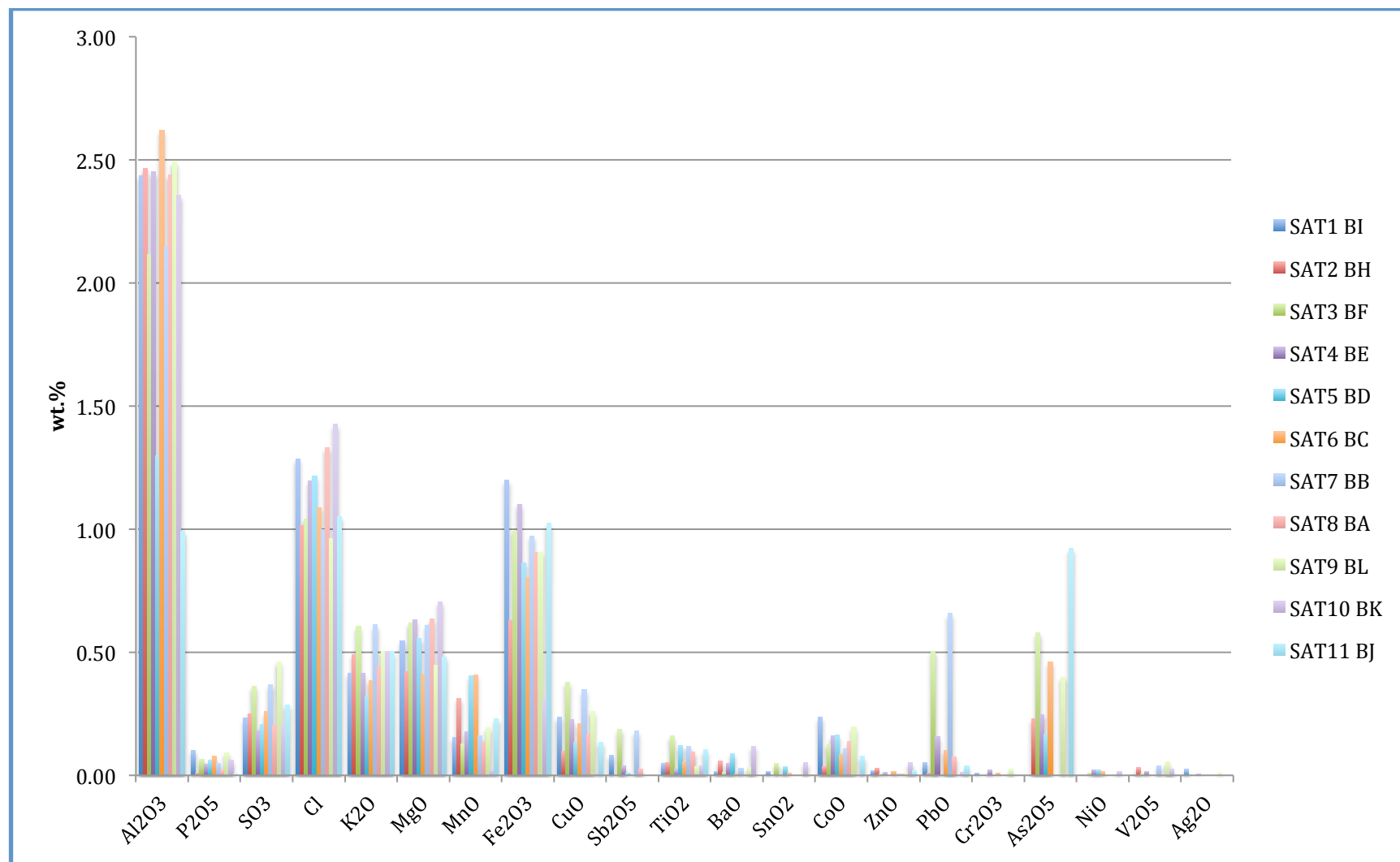


Figure 4



Appendix B – Correlations Between Elements

The figures showing the correlations between elements are formatted horizontally on the following pages.

Figure 5

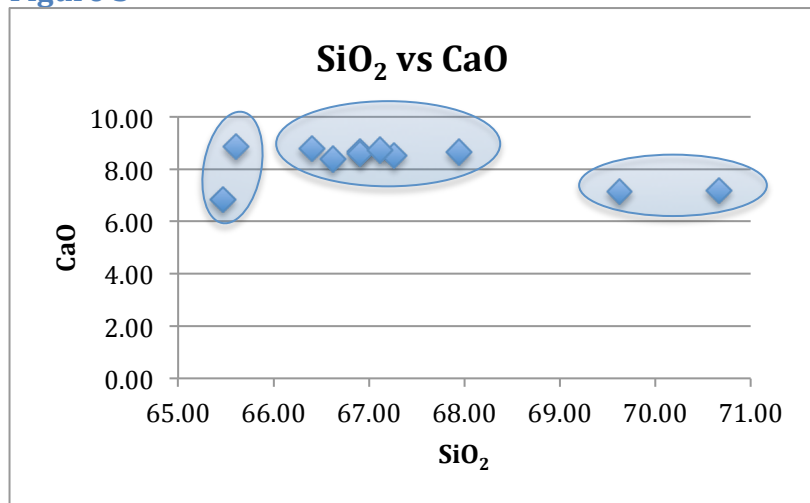


Figure 6

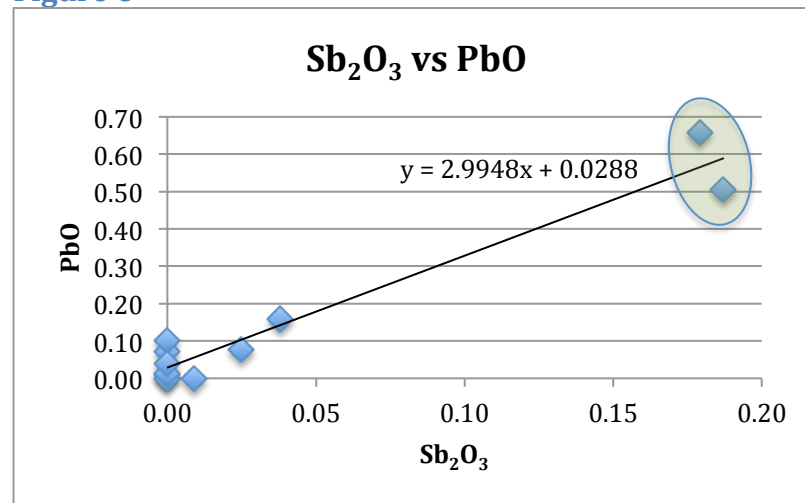


Figure 7

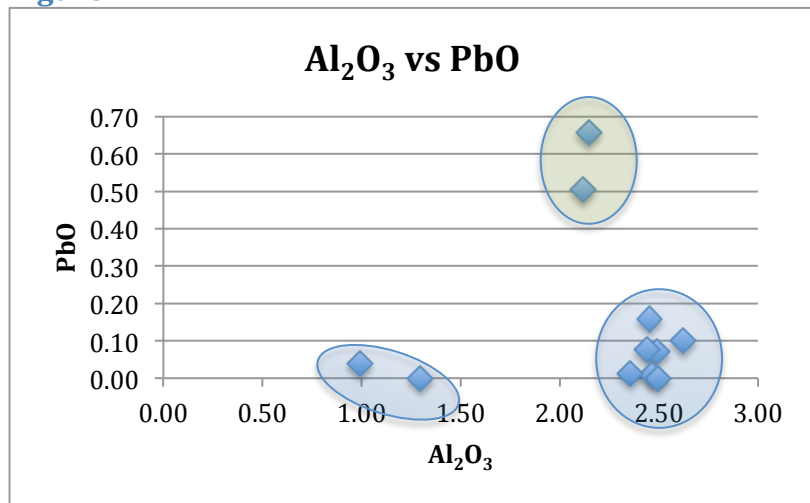


Figure 8

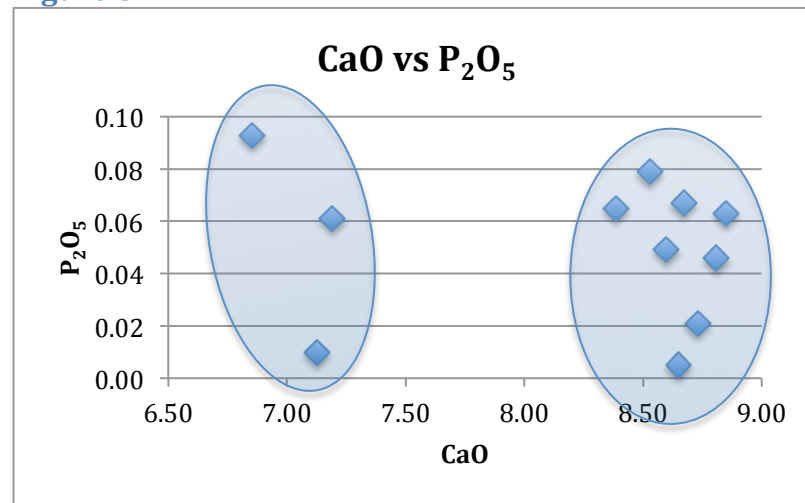


Figure 9

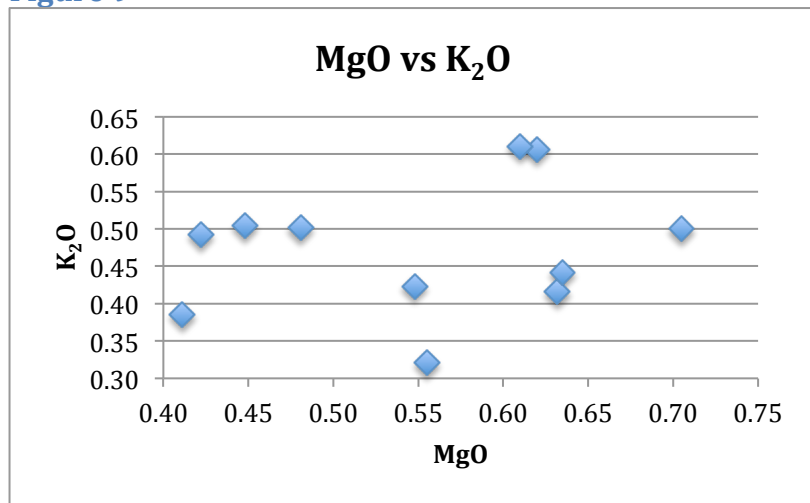


Figure 11

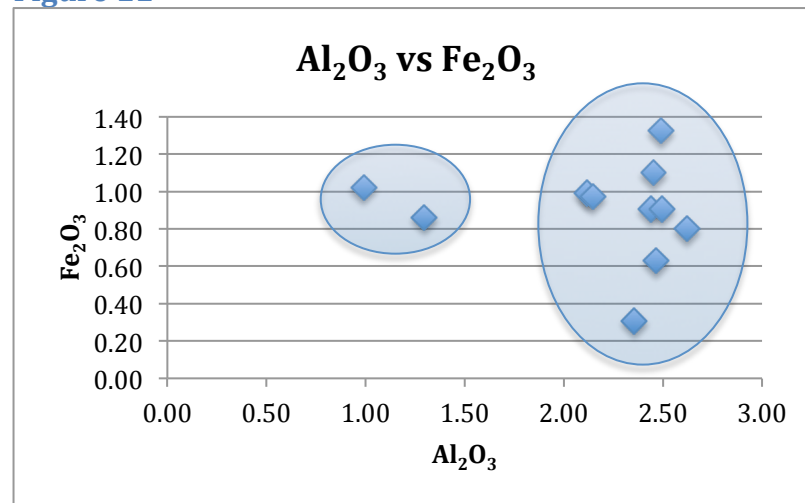


Figure 10

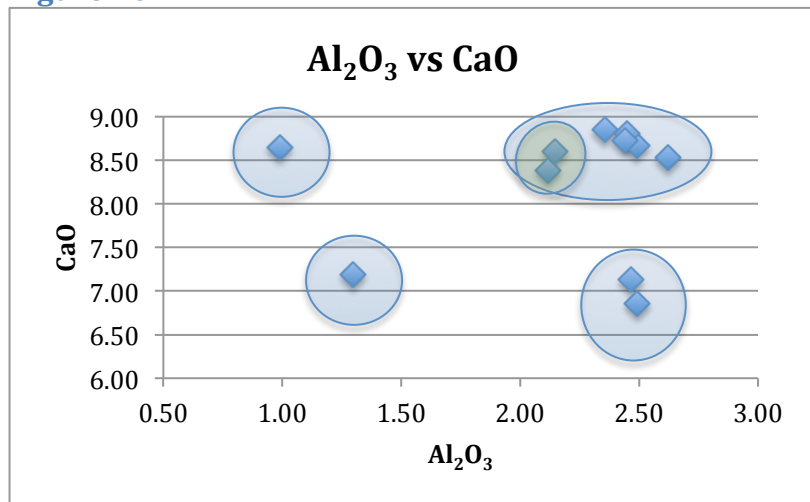


Figure 12

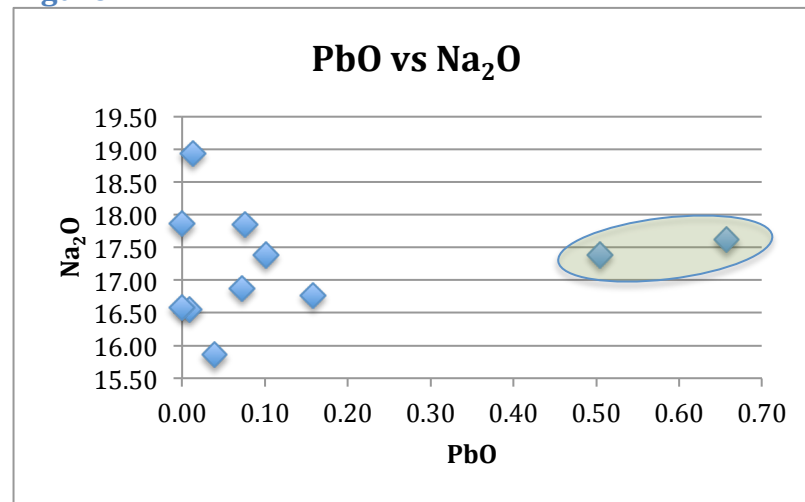


Figure 13

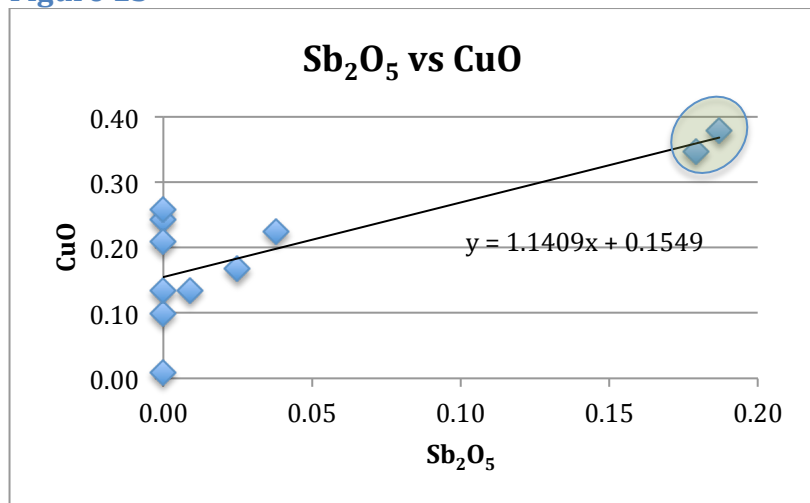


Figure 15

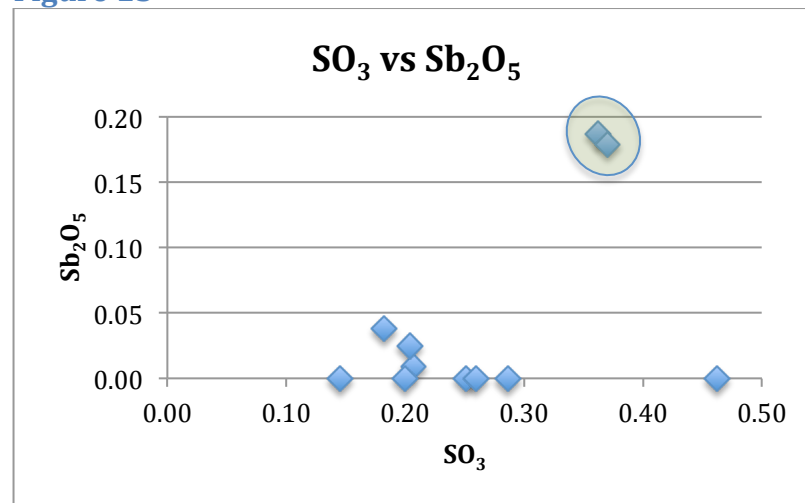


Figure 14

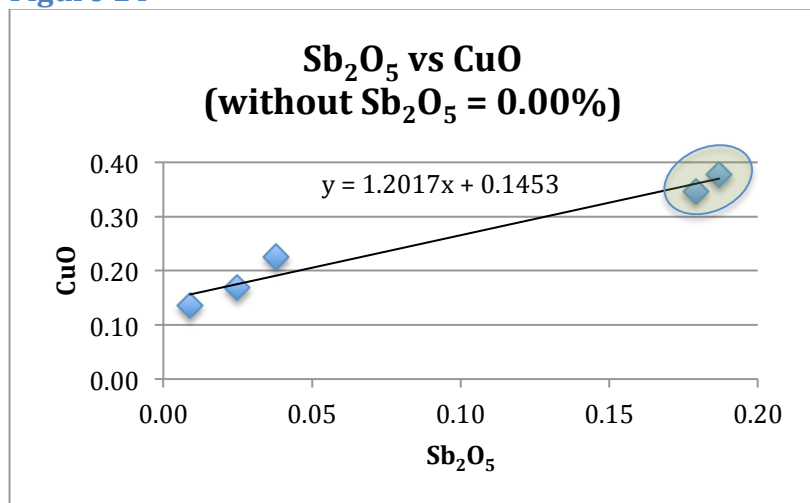


Figure 16

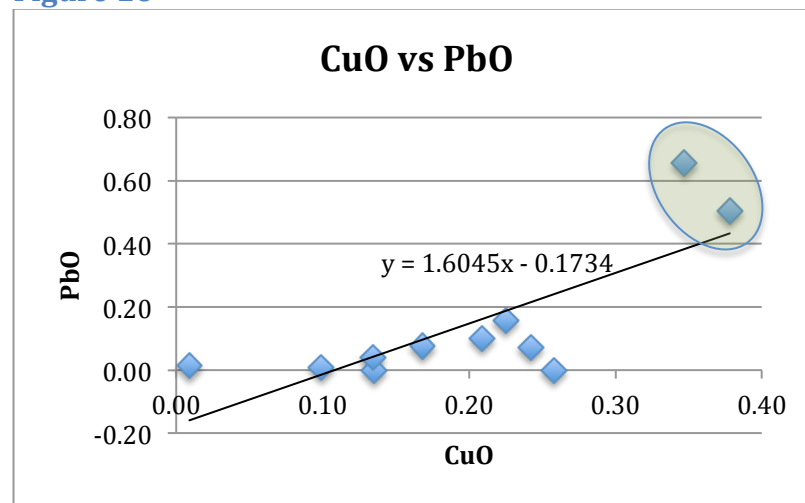


Figure 17

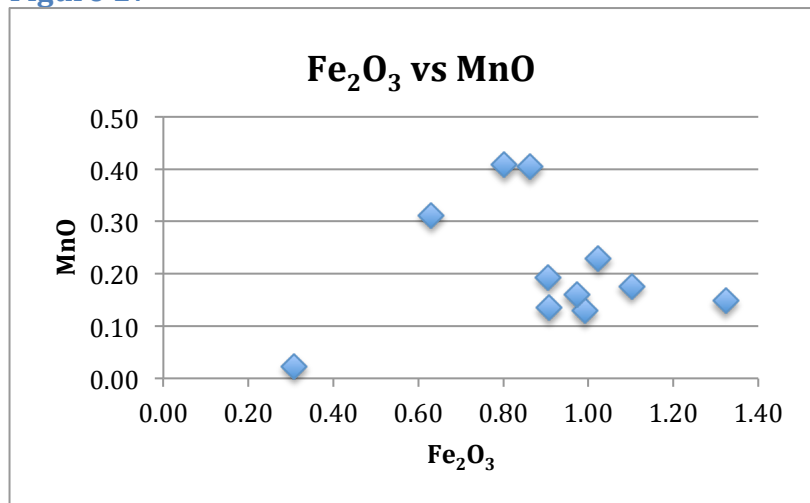


Figure 19

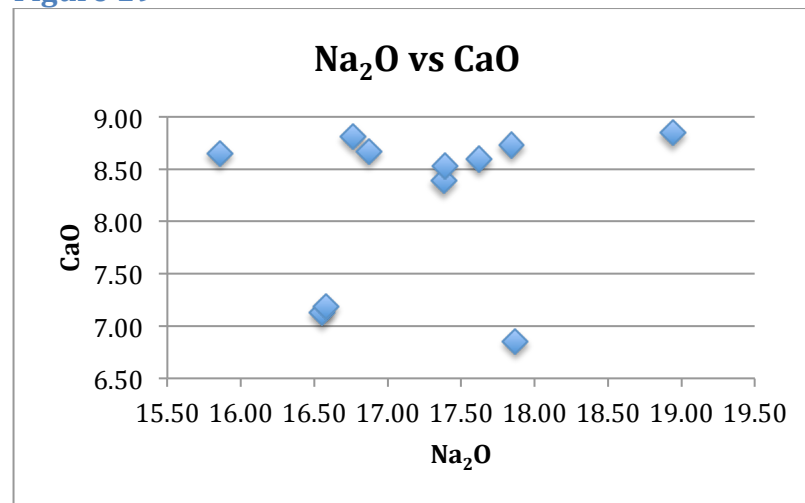


Figure 18

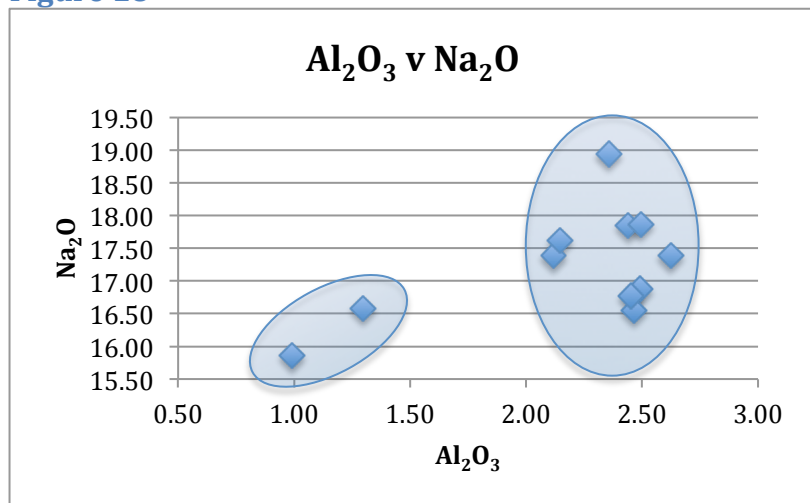


Figure 20

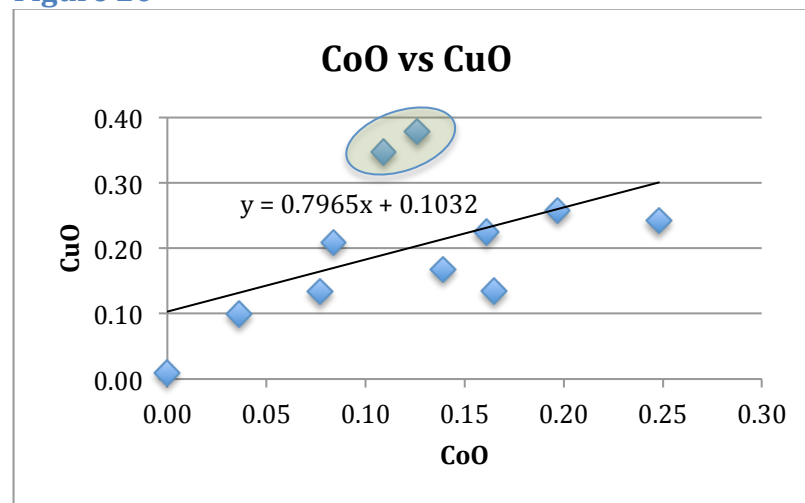


Figure 21

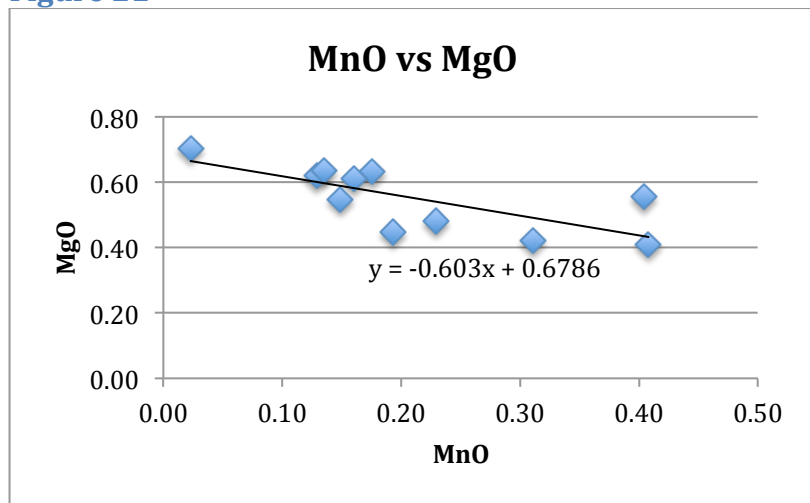


Figure 23

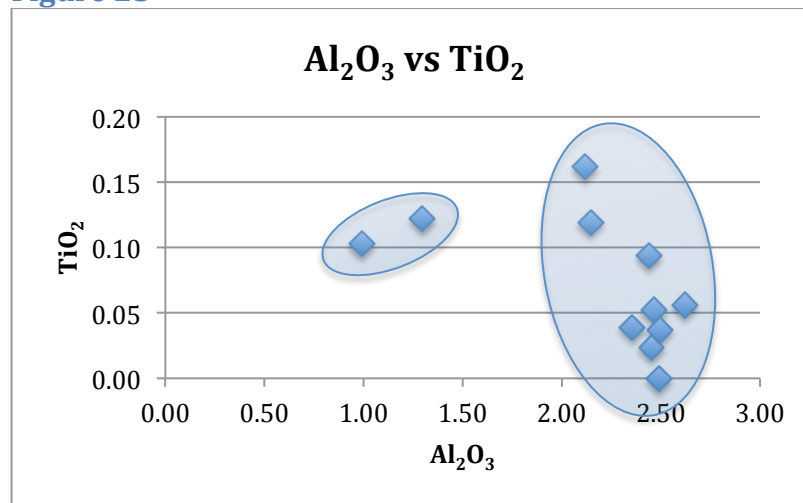


Figure 22

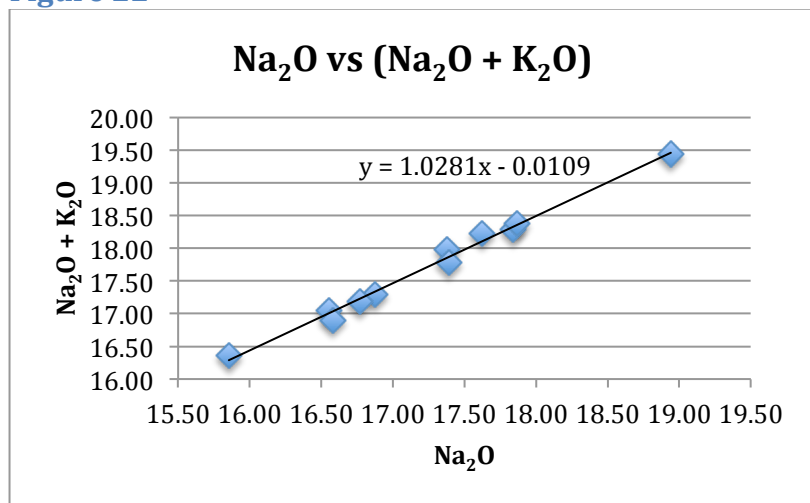


Figure 24

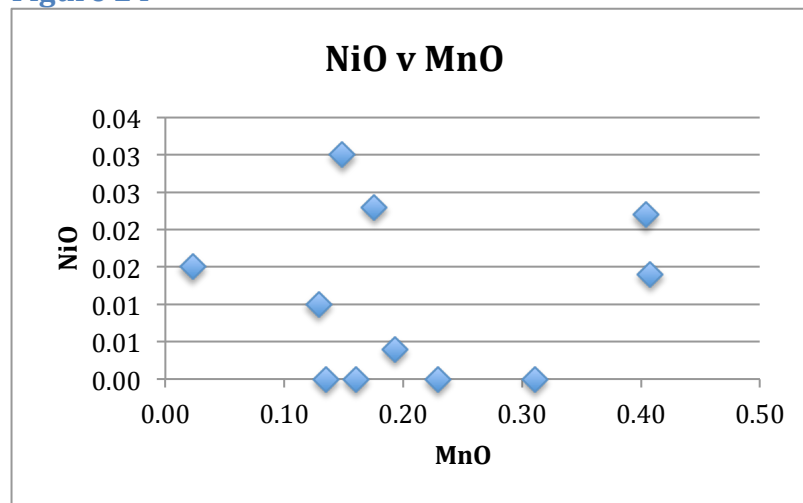


Figure 25

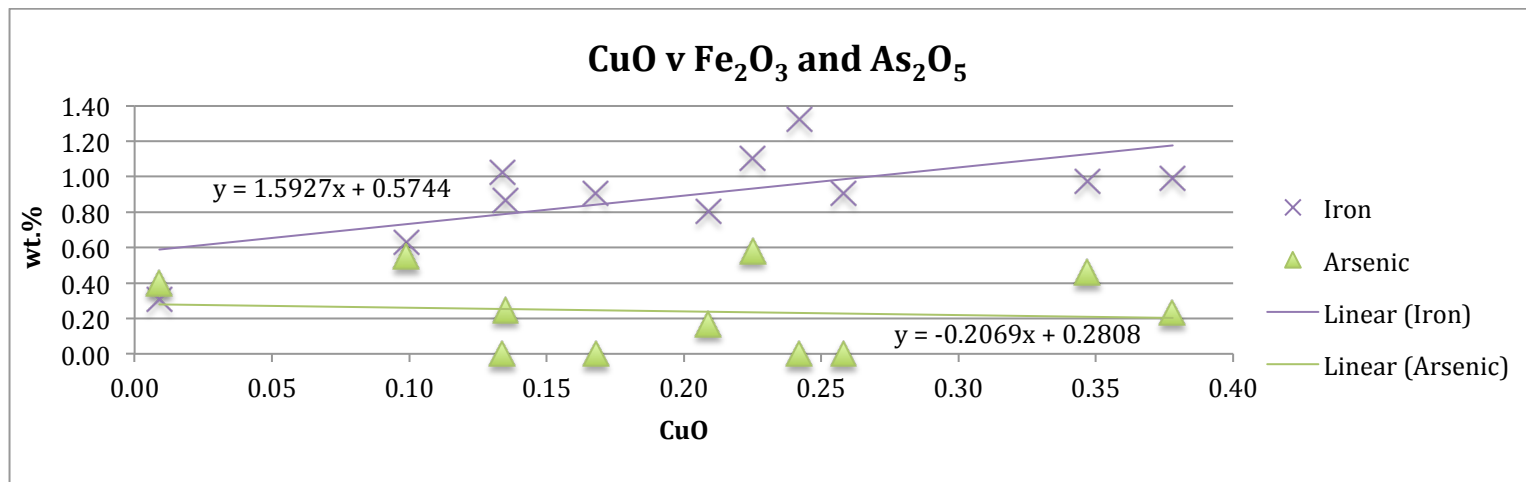


Figure 26

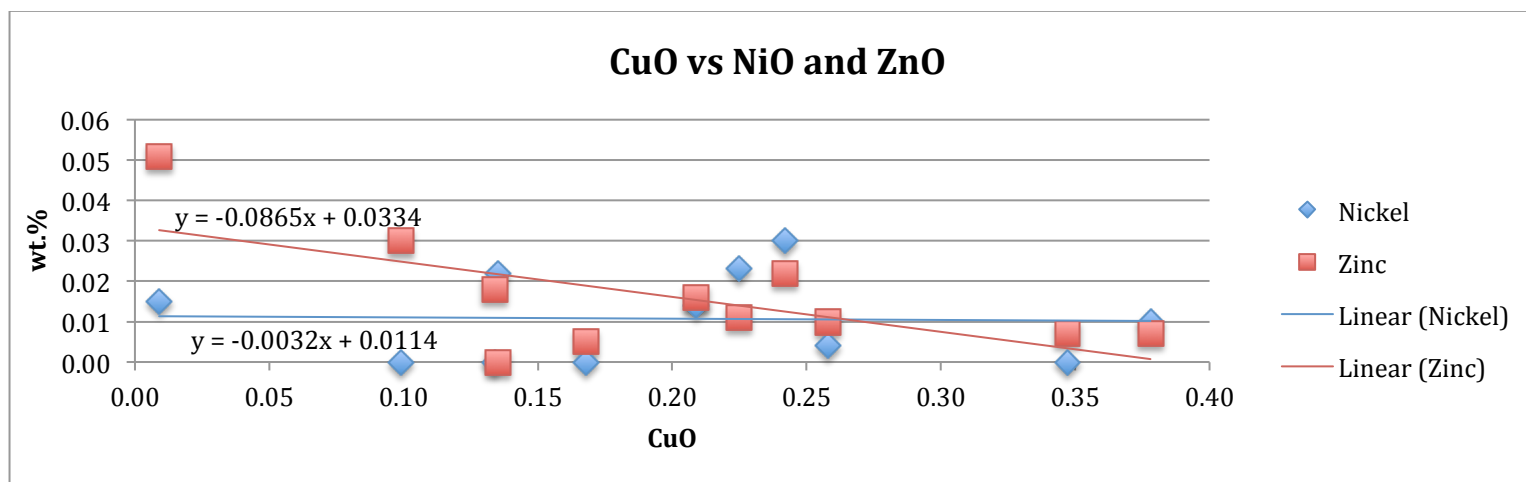


Figure 27

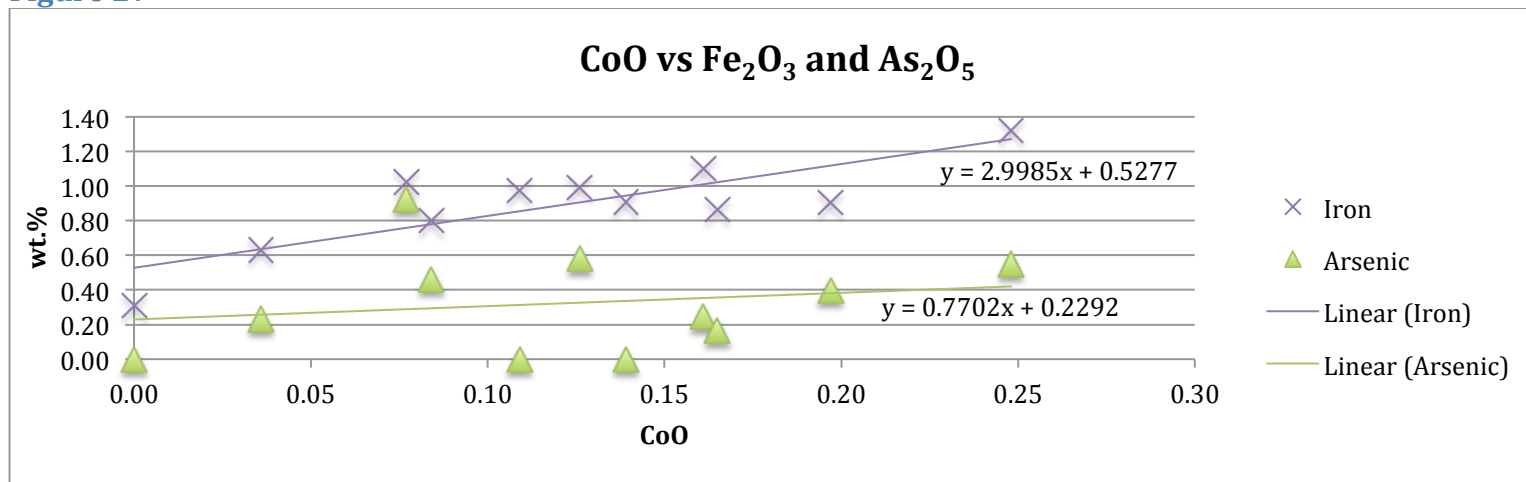
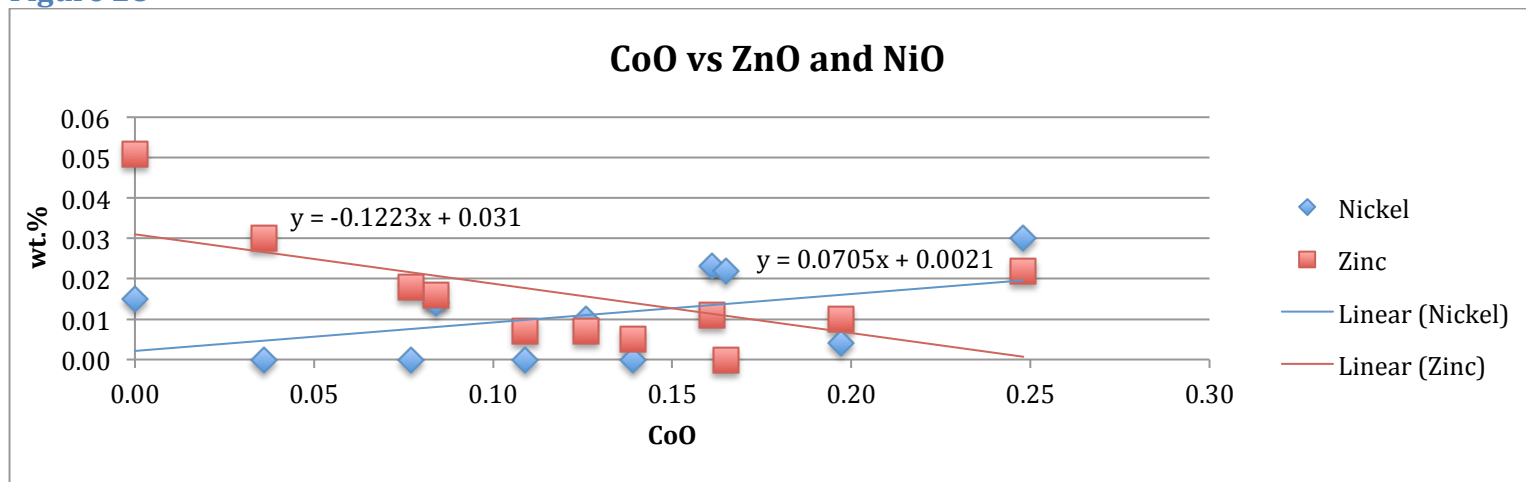


Figure 28



Appendix C – Contemporary Data

The data for glass analyzed by Aerts *et al.* (2000, 114), Henderson (2013a, 91-7), Towle and Henderson (2007, 51), and Turner (1954, cited in Henderson 1985, 271) are formatted horizontally on the following pages.

Figure 29

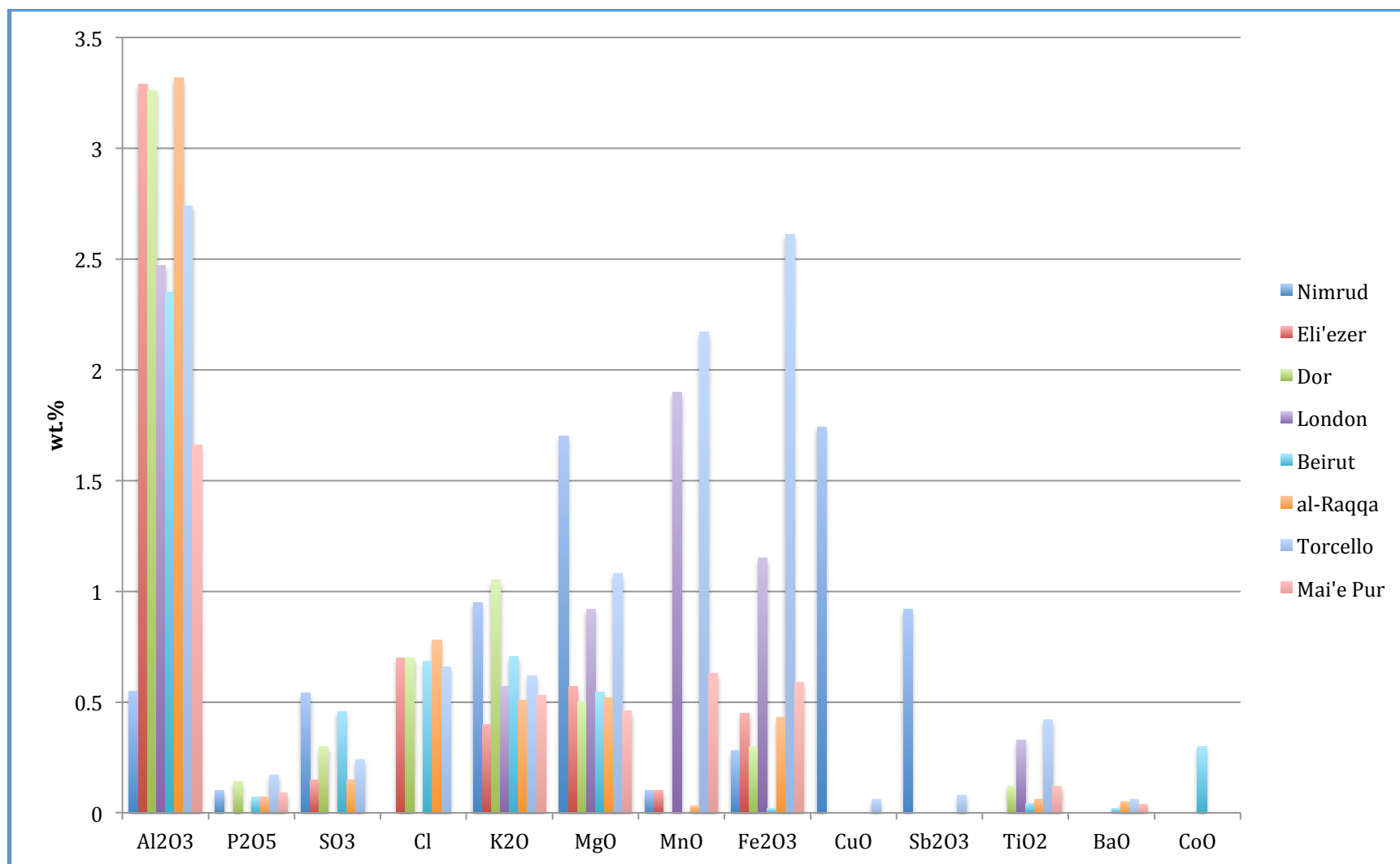


Figure 30

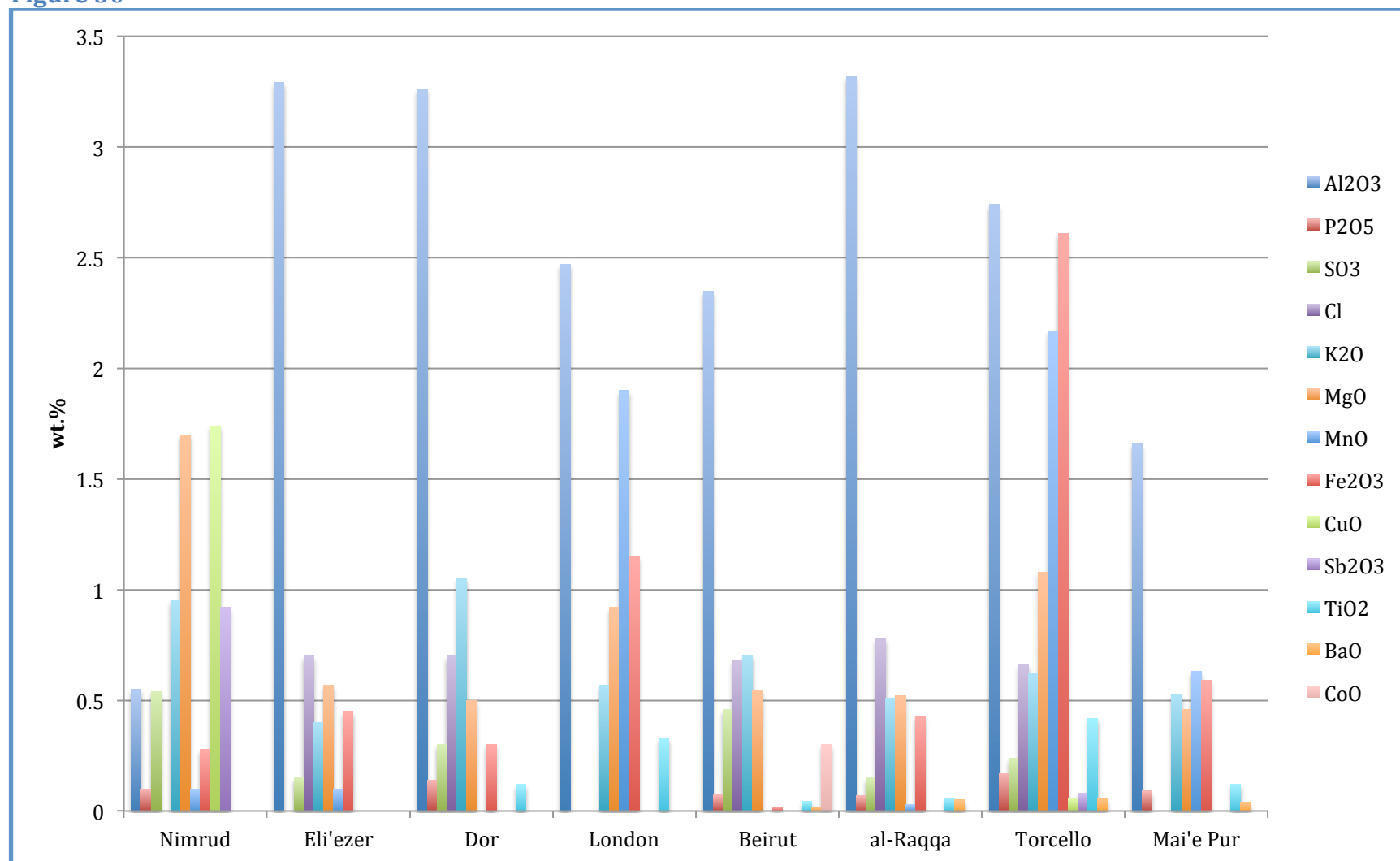
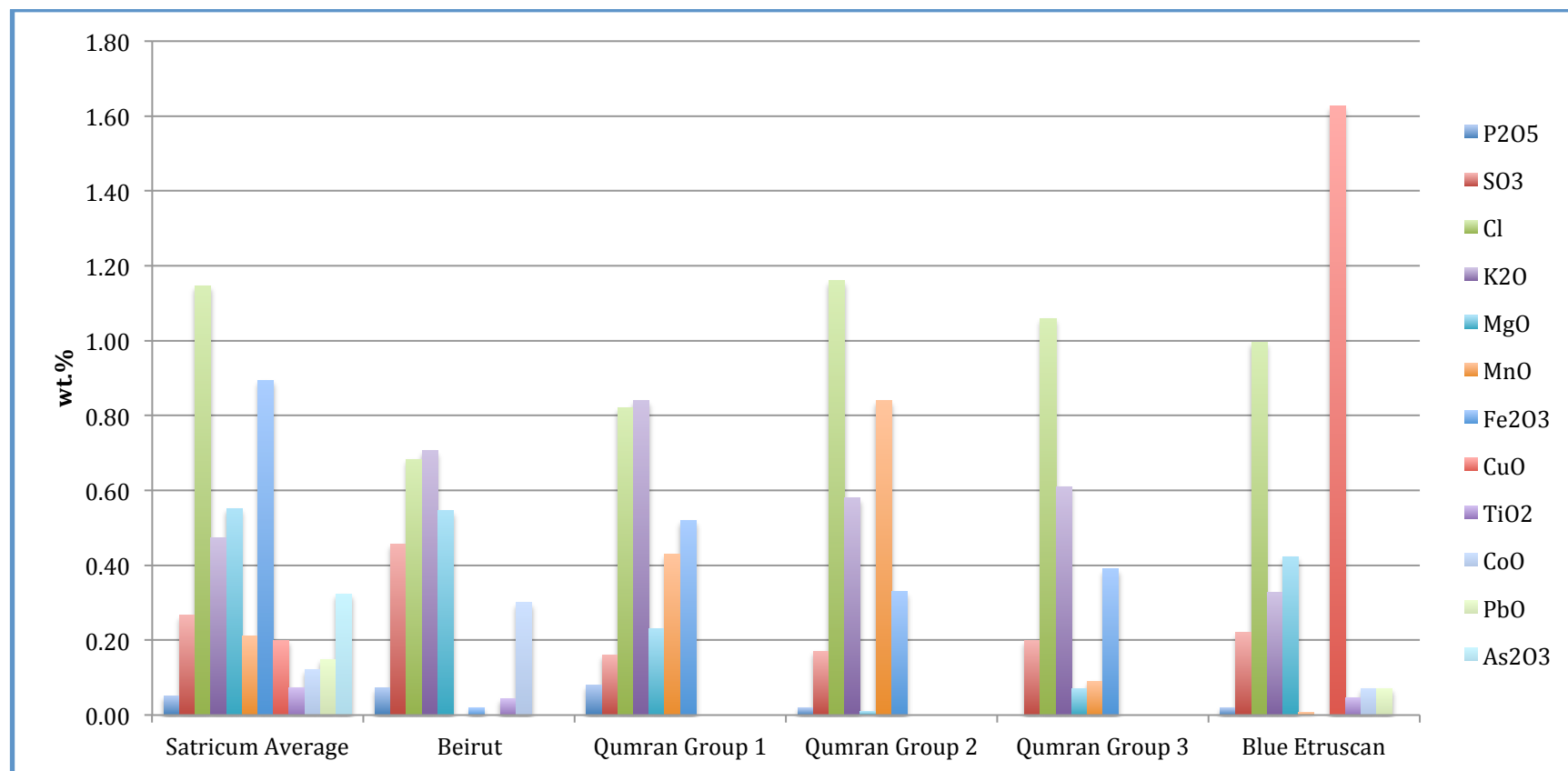


Figure 31



Appendix D – Images



Image 1 – “Rome and Environs”



Image 2 – “Mater Matuta’s Temple”

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