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Decoding the Network of Glass Production: A Meta-Analysis of Bronze Age Glass

By

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- The following dissertation is my own original work.
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- All assistance received has been acknowledged.



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ABSTRACT

Egyptian, Mesopotamian and Mycenaean glass are all examples of the High Magnesium Glass composition and the ability to distinguish between these three groups has, so far, been limited. The principle methods used for differentiating between production zones for Late Bronze Age glass has been through trace element or isotopic analysis. Major/minor elemental analysis, while more readily available, is restricted in its ability to separate between different production zones. This dissertation will examine the use of meta-analysis of major/minor elemental data of Bronze Age plant ash glass as well as the application of ratios and Principal Components Analysis and how this might be able to separate between production zones. This will be considered in relation to colour, which is a key factor of ancient glass. This dissertation will find potential evidence for the independent production of glass for shipping to Mycenaean Greece, identified through the use of ratios. It will also show that Principal Components Analysis may be useful in identifying relationships between elements and key components, especially when used in concurrence with bi-plots. This shall hopefully lay the groundwork for future use of PCA and ratios in the provenance of early glass.

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List of Abbreviations

EH	Early Helladic	B	Boron
MM	Middle Minoan	Na	Sodium

LM	Late Minoan	Mg	Magnesium
LH	Late Helladic	Al	Aluminium
LBA	Late Bronze Age	Si	Silicon
HMG	High Magnesium Glass	K	Potassium
LMG	Low Magnesium Glass	Ca	Calcium
LMHK	Low Magnesium High Potassium	Mn	Manganese
PCA	Principal Components Analysis	Fe	Iron
wt%	Weight Percent	Co	Cobalt
		Ni	Nickle
		Cu	Copper
		Ge	Geranium
		P	Phosphorus
		As	Arsenic
		O	Oxygen

1 INTRODUCTION

Glass is a complex material, muddled by the myriad of impurities associated with the key components of glass production (the network former, modifier and stabiliser) (Fernández-Navarro & Villegas 2013, 8). Early glass tended to be a highly coloured and prestigious material and was part of the gift exchange network between kingdoms (Bachhuber 2006, 349). In the Bronze Age, High Magnesium Glass (HMG) was produced in Egypt and Mesopotamia, which appear to be the origin of the glass used in Mycenaean Greece (Walton et al. 2009, 1502). In addition, a further glass

composition has been identified in Italy, which is a mixed alkali glass (Nightingale 2008, 75). Its use varied, from vessels to beads to architectural inlay, with certain functions such as beads, allowing glass to take culturally specific meanings (Eder 2012, 22). There has been little evidence that major/minor analysis can be used to provenance glass (Shortland and Eremin 2006, 598). On average, it can be seen that Mesopotamian glass has higher potash but this cannot be used to distinguish between it and Egyptian glass (Jackson & Nicholson 2010, 297). Isotopic and trace element analysis has been carried out by Waltron et al. (2009) and Henderson et al. (2009), which can be used to provenance glass to either an Egyptian or Mesopotamian source.

This dissertation uses published data on Bronze Age glasses to perform meta-analysis as well as unpublished data from Professor Julian Henderson (University of Nottingham). The benefit of this is a large data-set which might not otherwise be available due to the fragile and finite nature of the material. The use of large data-sets may be able to more firmly identify trends seen in different glass types and may be especially useful for a deeper analysis into different coloured glass. This dissertation will consider key elements such as potassium, magnesium and calcium and their variation between groups. This is especially in relation to cobalt glass and Mycenaean glass, which show interesting variation from the bulk of the Egyptian glass composition. This dissertation will also look at the application of Principal Components Analysis (a method for reducing the dimensions of large data sets) and how it might be used for the analysis of ancient glass. The use of colour shall also be considered, as colour is an integral part of glass. While this dissertation has a significant focus on the analysis of published data, it is hoped that it will highlight the importance of meta-analysis in the study of ancient glass, as well as the importance of considering how an array of techniques may be useful in concurrence with each other.

2 THE COMPOSITION OF BRONZE AGE GLASS AND THE ORIGINS OF GLASS TECHNOLOGY

2.1 WHAT IS GLASS

Glass is an amorphous solid composed of three primary ingredients. The *network former* of glass is typically silica (SiO_2) although in more recent years glass can be made with other network formers (B_2O_3, GeO_3, P_2O_5, As_2O_5 and As_2O_3) (Pollard & Heron 2008, 149). This is the building block of glass which forms the matrix of the compound. Due to the high temperatures needed to melt silica (1 700^oC), a *flux* or *network modifier* is required (Henderson 2013, 2). An alkali such as soda (Na_2O) or potash (K_2O) lowers the melting point of silica by weakening the siloxane bonds (Fernández-Navarro & Villegas 2013, 8). This brings the melting temperature down to around 1 000 ^oC (Goffer 2007, 115). In the past, there have been three commonly used sources to provide the flux, namely sodium plant ash, potash plant ash and Egyptian natron (Moretti & Hreglich 2013, 29). Using only these two ingredients leads to an unstable glass which could easily dissolve in water (Shortland & Eremin 2006, 590). A third component is required and this is the *network stabiliser*, a type of network modifier that helps to stabilise the compound. Earth-alkaline metals bond with the non-bridging oxygen ions which helps to counteract the breakdown of the glass (Fernández-Navarro & Villegas 2013, 8). Lime (CaO) is frequently used as a stabiliser, either in the form of plant ash or as seashells (Henderson 2013, 5). Other stabilisers include alumina, which can be introduced as an impurity in the silica source, or magnesia which like lime can be an impurity included in the plant ash (Moretti & Hreglich 2013, 30).

The basic composition of Bronze Age glass is the soda-lime-silica glass. However, it is a much more complex material with around 10-12 compounds over 0.1 wt% coming primarily from the two main components – silica and plant ash (Rehren & Puschen 2008, 19). The silica source is generally believed to have come from either crushed quartz or a quartz sand (Henderson et al. 2018, 71). This

is because of the relatively low levels of associated impurities such as calcite, magnesia, alumina and iron oxides (Moretti & Hreglich 2013, 29). Further, there has been archaeological evidence which supports the use of quartz. The site of Qantir has evidence for the processing of quartz with hammers and grinding tools found alongside quartz pebbles (Rehren & Puschen 2008, 22). At Amarna, a layer of quartzite pebbles have been found in what has been interpreted as a furnace bed, potentially suggesting the use of heat treatment to make it easier to crush the pebbles in preparation for glass making (Shortland & Eremin 2009, 589). Using quartz, the associated impurities (Al, Ti, Fe) can be as low as 0.5 wt%, while in contrast Egyptian and Near Eastern sands tend to have higher alumina (c. 1-4 wt%) and can also introduce high levels of lime (Degryse & Shortland 2020, 6; Tite et al. 2002, 586). On the other hand, some Egyptian mature sands can have a similar composition to quartz, meaning their use cannot be entirely dismissed (Shortland & Eremin 2009, 589). One further case supporting the use of quartz is found at Qantir, where low levels of gold has been found in some red glasses, perhaps suggesting that a gold-bearing quartz was processed for gold and the by-product (quartz dust) was then used in glass production (Rehren & Puschen 2008, 22).

Plant ash meanwhile provides both the network modifier and stabiliser (Nightingale 2018, 30). This is in contrast to natron, which is a relatively pure source of soda and so requires the addition of stabilisers, often in the form of an impure silica source which provides Ca and Al (Moretti & Hreglich 2013, 29). The dominant alkali in glass can suggest the type of plant used, for instance the predominance of soda suggests halophytic plants such as *Salsola* and *Salicornia* (Shortland & Eremin 2006, 589). As well as being a source of alkali, plant ash also has other associated impurities such as Ca, and magnesium (Mg) (Walton et al. 2009, 1499). The plant ash used in the Bronze Age is known as High Magnesium Glass (HMG) in contrast to the later Low Magnesium Glass (LMG) which is formed using natron instead of plant ash (Duckworth 2011, 42). Natron was used as a flux as early as the eighteenth-century B.C. but began to be used more regularly from around the 1st millennium B.C. (Gallo et al. 2013, 2597; Moretti & Hreglich 2013, 29). In contrast to plant ash, natron is

relatively pure, typically having magnesia, potash and lime levels below 1 wt% (Tite et al. 2002, 586). Other alkali glasses include mixed alkali glass and potash glass. An example of mixed alkali glass comes from Frattesina. These have both potash and soda as well as low levels of lime and magnesia (Tite et al. 2006, 1284). It has been suggested that these glasses may have derived from a different plant source, one of which has higher levels of potash (Degryse & Shortland 2020, 2).

A final component that, although not required for the glass matrix, is still of great significance are the colourants and opacifiers. Colourants are transition element ions and add colour to the glass (Biron & Chopinet 2013, 52). Some colourants can enter as an impurity, such as iron which gives a blue-green colour (Jackson & Nicholson 2010, 297). However, many colourants such as copper or cobalt were purposefully added to achieve coloured glasses (Smirnious & Rehren 2013, 4743). The majority of early glass is coloured, with colourless glass being far less common (Wood & Hsu 2019). Opacifiers are small, often crystalline, particles that have a different reflective index to the glass matrix which they are in (Biron & Chopinet 2013, 59). Antimony and tin are examples of some opacifiers and have been used in conjunction with calcium or lead (Biron & Chopinet 2013, 59; Goffer 2007, 123). The use of colourants and opacifiers make glass a colourful and diverse material.

2.2 Early Vitreous Materials

Before the discovery of glass, various other vitreous materials were in use, starting from the 4th millennium B.C. including glazed stones, faience and Egyptian blue (a type of frit) (Tite & Bimson 1989, 87). Glazed stones were frequently produced using steatite or quartz, fluxed with an alkali (Tite et al. 2006 1284). As steatite is a soft stone (with a Mohs hardness of 1) it would have been easier to carve prior to firing, which hardens it (Nicholson 2012, 13). Its softness is due to its composition which is predominantly a fine talc ($Mg_3\ Si_4\ 0_{10}\ (OH)_2$) (Tite & Bimson 1989 87). Firing steatite is known from pharaonic Egypt and produces a hardened stone, regardless of glazing (Nicholson 2012, 13). By analogy with faience production, it has been suggested that glazed stones may have been produced by firing the stone in a glazed mixture or by coating the stone with a raw

or fritted glaze (Tite & Bimson 1989, 87). Experimental work carried out in 1962 suggests that malachite and powdered wood ash or natron would be enough to give a quartz crystal a blue glaze, although earlier theories connected the glaze with copper used in metallurgy (Nicholson 2012, 13-14). Similar to glazed stones, faience is composed of a ground quartz body and an outer glaze (Tite et al. 2002, 585). While faience is not as easy to glaze as stone, it is much easier to shape and moulds can be used (Nicholson 2012, 15). Like glass, it appears that soda-rich plants were used as flux, although evidence from Crete and Western Europe appear to suggest local production using a mixed alkali source (Tite et al. 2006, 1284). While both steatite and faience were used in the 4th millennium B.C., the earliest Egyptian blue (a frit) appears around a millennium later (c. 2613-2181 B.C.) (Panagiotaki 2008, 36). Egyptian blue, as well as being suitable for beads, can be used as a colourant on wall paintings or as inlay, as seen on a game board discovered in Knossos (Nightingale 2012, 31; Panagiotaki 2008, 45). Faience arrives in Crete around EM II (the earliest example coming from Mochlos) and Egyptian blue during the transition from EM to MM IA (Colburn 2008, 112; Panagiotaki 2008, 36).

The earliest man-made Bronze Age glass are beads and date to around 2500 B.C. (Henderson 2013, 8). The first discovery of true glass is hard to identify but is believed to have originated in Mesopotamia (Duckworth 2011, 11). Glass and the knowledge of its production is believed to have been brought to Egypt during the campaigns of Thutmose III (Nicholson 2012, 19). As some of the words used to discuss glass in the Amarna letters come from the Akkadian or Hurrian, it is believed that this further suggests that glass was imported into Egypt (Wood & Hsu 2019). Recent critique of the evidence for a Mesopotamian origin of glass making by Shortland et al. (2018) has shown that it may not hold up to scrutiny and Egypt has equal claim (Shortland et al. 2018, 781). It is suggested that glass was viewed as a man-made stone for instance the Akkadians refer to '*lapis lazuli from the kiln'* and in Egypt glass is known as '*stone of the kind that flows*' (Nicholson 2012, 17-19). The major producers of glass during the Bronze Age were Egypt and Mesopotamia (Smirnious & Rehren 2013, 4732). It has been suggested that glass may have been produced by other kingdoms (i.e. Hittite &

Mycenaean) although there has yet to be any conclusive evidence as primary production is difficult to prove (Henderson et al. 2018, 70). For now, the only evidence of primary production has been found in Egypt although cuneiform tablets from Mesopotamia suggest primary production was also occurring here (Walton et al. 2009, 1497).

2.3 Glass Production and Trade in the Bronze Age

Primary production is the fusing of raw materials to produce glass while secondary production involves the melting of glass to produce objects (Duckworth 2011, 14). Raw ingredients would have to be gathered, as well as fuel for the furnace (Barkoudah & Henderson 2006, 301). In some glass productions the plant ash may have been first purified, which helps to reduce impurities such as calcium, magnesium and silico-aluminates (Moretti & Hreglich 2013, 30). There is evidence for the use of fritting in LBA glass, which is an intermediary step in glass production, which removes bubbles (Wood & Hsu 2019). The presence of frit in furnaces can be seen as evidence of primary glass production, this is because the presence of glass working may just indicate secondary production (Henderson et al 2018, 70). The addition of colourants is believed to have occurred either during or after fritting, with Amarna providing evidence of cobalt blue frit (Duckworth 2011, 44; Wood & Hsu 2019). Frit is reheated to make glass proper (Wood & Hsu 2019).

While the production of glass may have been limited to a few select areas (and certainly under palatial control), glass-working occurred in multiple locations (Shortland et al. 2007, 781). For this to happen, glass had to be transported between production zones. Glass is believed to have been part of the gift-exchange network recorded in the Amarna letters (Pulak 2012, 868). Archaeological evidence for the transport of glass as ingots has been found on the Uluburun shipwreck, located off the coast of Turkey (Panagiotaki 2008, 47). The ultimate destination of the ship is unknown but based on its cargo, location and wind direction, it is believed that the Uluburun was heading towards mainland Greece (Walton et al. 2009, 1497). The shipwreck contained 350 kg of glass ingots, which are predominantly cobalt blue (lapis lazuli) and light blue (turquoise), while

there are only three ingots for both purple (amethyst) and brown (amber) (Pulak 2012, 868). This shows clear evidence for the transport of glass across the Bronze Age Mediterranean.

Another way to identify the trade of Late Bronze Age glass is through compositional variation between production zones. Using scientific analysis, it is possible to identify different quantities of elements and thus categorise the glass geographically. Variation of glass composition is caused by a range of factors such as the composition of raw materials (affected by geological origin, type, i.e. plant type, sand/quartz…) or preparation (proportions of raw materials, addition of colourants, partial melting…) (Henderson et al. 2009, 3). Results are typically either in weight oxide percentage (wt%) or parts per million (ppm). Another way to provenance glass is through the use of isotopic ratios – for example $^{87}Sr/^{86}Sr$ ratio and $^{143}Nd/^{144}Nd$ ratio (Henderson et al. 2009, 7).

There have been different levels of success when differentiating between the origins of glass. There is very little evidence that major/minor elemental analysis can distinguish between production zones although general trends can be made, such as higher potash in Mesopotamian glass (Jackson & Nicholson 2010, 297). Further generalisations can be made using colourants and their associated impurities (Shortland & Eremin 2006, 598). For example, cobalt blue glass is generally considered to have come from Egypt, although examples from Mesopotamia are not unknown (Shortland et al. 2007, 786). A further example is the tin to copper ratio, indicating the use of bronze, which has been linked to an Egyptian origin while Mesopotamia favoured a purer source of copper (Shortland et al. 2007, 786). Mesopotamian glass has on average lower iron, aluminium and titanium than Egyptian glass but again, this is a generalisation and cannot be

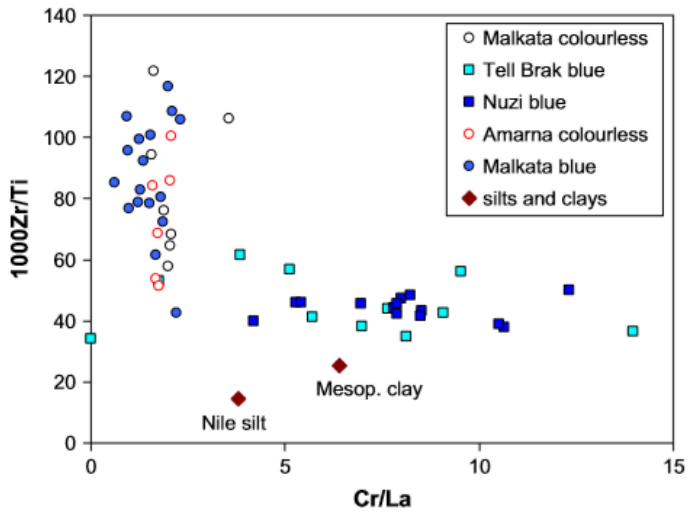


Figure 2.1: Trace Element Ratios distinguishing between Mesopotamian and Egyptian glass from Shortland et al. (2017, 788)

used to firmly provenance a glass object (Kempt et al. 2017, 168). The use of trace elements identified using LA-ICP-MS has been more successful in distinguishing Mesopotamian and Egyptian glass. Graphs plotting Cr/La against 1000Zr/Ti against each other offer a much clearer distinction between the two glass sources, with Mesopotamian glass having relatively constant Zr/Ti and variable Cr/La and Egyptian glass vice versa (See Figure 2.1: Trace Element Ratios distinguishing between Mesopotamian and Egyptian glass from Shortland et al. (2017, 788)) (Shortland et al. 2007, 788). An example of the use of trace element analysis has been on the Uluburun, where analysis suggests that the glass came from Egypt (Jackson & Nicholson 2010, 299). Meanwhile isotopes can also be used to provenance glass. Isotopic differences reveal Mesopotamian glass has low levels of Nd but reasonably high ratios (between 0.51233 and 0.51253) of $^{143}Nd/^{144}Nd$ and no correlation with Sr while Egyptian glass has a low ratio of $^{143}Nd/^{144}Nd$ (0.51215 to 0.51224) and correlation between Nd and Sr (Henderson et al. 2009, 7).

2.4 Bronze Age Glass Compositions

During the Bronze Age, there are several different glass types that emerge. The most prominent of these is HMG, which makes up the bulk of the glass from Mesopotamia and Egypt (Nikita & Henderson 2006, 72). The two other glass compositions appear towards the end of the Bronze Age, although there is evidence of earlier use. Mixed alkali glasses have been found across Europe, with the greatest concentrations in Switzerland and Northern Italy (Henderson et al. 2015, 2). The site of Frattesina has evidence of significant glass working, although definitive evidence for primary production has yet to be found (Henderson et al. 2015, 3). Bronze

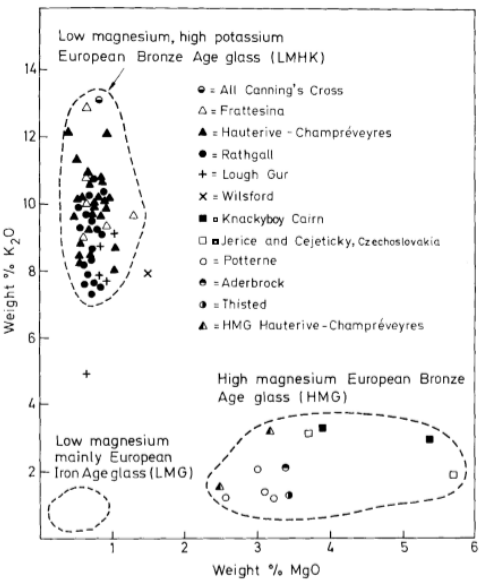


Figure 2.2: Glass Compositions in Prehistoric Europe (Henderson 1988, 447)

Age Mixed Alkali glass can be categorised as low magnesium, high potassium (LMHK) as demonstrated in Figure 2.2: Glass Compositions in Prehistoric Europe (Henderson 1988, 447) (Henderson 1988, 447). Natron glass is a LMG and while predominant in the Iron Age, examples have been found in the Late Bronze Age (Duckworth 2011, 42). There has been some suggestion that natron may have been used in the production of cobalt blue glass in Bronze Age Egypt, although this is debated (Wood & Hsu 2019).

2.4.1 High Magnesium Glass

HMG derives its high levels of magnesium from the use of plant ash which also introduces elevated levels of potash (Duckworth 2011, 42). As seen in Figure 2.2, the levels of magnesia can reach up to 6 wt% and do not tend to drop below 2 wt%. On average, above 1 to around 4 wt% potash is seen in high magnesia glasses. While plant ash also introduces other impurities such as calcium, this is not a good way to distinguish between glass types as calcium can be included in the silica source, or as an independent addition (Duckworth 2011, 39). This glass sees reduction in use by the end of the Bronze Age and was replaced by natron.

2.4.2 Low Magnesium, High Potassium Glass

The earliest evidence (to date) of mixed alkali glass comes from chalcolithic France (Towle et al. 2001, 9). Towards the end of the Bronze Age, mixed alkali glass is found in multiple locations such as Sweden, Italy, Germany, Bohemia and Britain (Henderson et al. 2015, 1). This glass is characterised by having high levels of sodium and potassium (hence mixed alkali) and low levels of calcium and magnesium (Henderson 2013, 183). It has been suggested that purified plant ash may have been used as this would reduce impurities – such as calcium and aluminium – but this would require a significant history of ash purification (Henderson 2013, 186). As such, it may be suggested that reasonably pure ingredients were used (Henderson et al. 2015, 2).

2.4.3 Low Magnesium Glass

Like HMGs, LMGs have high levels of soda although importantly they can be distinguished by their low levels of magnesium and potassium, which are typically below 1 wt% (Tite et al. 2002, 586). This is due to the use of natron, which is a relatively pure source of sodium carbonate (Moretti & Hreglich 2013, 29). Like mixed alkali glass, natron glass is generally considered to have come into use around the end of the Bronze Age and is categorised more as an Iron Age composition (Nightingale 2008, 75). To make up for the low levels of stabilisers, which are normally included in the plant ash, natron-based glasses tend to use a less pure silica source, such as sand (Moretti & Hreglich 2013, 29). The earliest known examples of LMG date to the 13th to 12th centuries B.C. and are from Pella, in Jordan (Angelini et al. 2005, 32).

3 GLASS IN ARCHAEOLOGICAL CONTEXTS

3.1 THE AEGEAN

Glass was used by the Mycenaeans to make beads, as inlays on furniture, architecture and in some cases, as sword hilts (Jackson & Wager 2011, 116). While Bronze Age glass vessels have been found in Greece, these are all believed to be imports rather than manufactured locally (Nightingale 1998, 6). Unlike contemporary Bronze Age glass industries, the Mycenaeans appear to have focused on bead production (Nikita et al. 2006, 39). These beads can be sorted into two categories: simple and relief beads. Simple beads are without motifs and come in forms such as globular, disc or amygdaloid (Nikitia 2003, 28). It is difficult to identify where simple beads were produced as they were common across the Bronze Age kingdoms (Nightingale 2008, 74). This contrasts with relief beads, which were decorated with motifs making them culturally specific to the Mycenaeans (Hughes-Brock 1999, 290). These relief beads are considered a cultural hallmark and very few have been found outside of areas of Mycenaean influence (Eder 2012, 222). Motifs can be divided into

categories such as floral, faunal, abstract, object and human (Nikitia 2003, 28). Such motifs are also seen on relief plaques, which could be used as inlays on furniture (Nightingale 2018, 42). The beads themselves could be worn as necklaces, diadems and other items of jewellery, or sewn onto or used as weights on clothing (Hughes-Brock 1999, 280). Glass used in architectural decoration can be seen at Tiryns, where glass inlay was used in the gypsum blocks of large Megaron (Nightingale 2018, 42). The use of glass in swords ranges from inlay to full glass hilts, although it is believed that these would have been largely ceremonial (Nightingale 2003, 20). The glass used in the Aegean was predominantly blue (dark blue coloured by cobalt and light blue by copper) although other colours such as green, amber, purple and white are also known (Henderson 2013, 166).

As it can be seen, glass was used in a variety of ways in the Bronze Age Aegean. Despite the wide usage of glass, we do not have much to go on from written records. During the Greek Bronze Age, writing was limited to records such as the clay tablets found at Pylos and Knossos (Nightingale 1998, 213). The word commonly translated as dark blue glass is *ku-wa-no*, is similar to the Hittite *kuwanna* which could suggest it is a loanword (Walton et al. 2009, 1497). Some have translated *ku-wa-no* as lapis lazuli rather than glass, while others have translated it as referring to both materials with no modifier to distinguish between them (Nightingale 1998, 214; Nikita 2003, 25). This word appears in the Homeric epic as κύανος where it is usually used to describe objects ranging from black to blue and is generally attached to the supernatural (Nightingale 2008, 80). This term is also used to describe inlay in Alkinoos' Palace in the Odyssey, something seen at Tiryns (Panagiotaki et al. 2003, 16). No term has been linked firmly with light blue glass although pa-ra-ku has been suggested (Hughes-Brock 2011, 102).

Interpreting the meaning and worth of glass in the Bronze Age Aegean is no easy task. While glass is believed to have been a prestige item, its presence is found in a range of tombs of varying social status with the elite tending to have a greater quantity (Jackson & Wager 2011, 116). Due to the discovery of gold coated glass beads, it has been suggested by some that glass may have been used as a cheap alternative to gold although this is likely not the case as glass itself would have been

an imported commodity (Nightingale 2018, 37). It is possible that this practice combined apotropaic properties associated with both glass and gold, as suggested by Jackson & Wager (2011, 118). This is comparable to the Minoan and Early Mycenaean rings which were made from multiple metals despite only one metal being visible (Nightingale 2008, 81). This suggests a practice of combining apotropaic properties of materials.

Attempts have been made to unearth the properties associated with glass. Without written sources, we instead have to rely on deciphering the meaning of motifs and colours seen in Mycenaean glass. Comparisons can be drawn with contemporary cultures, such as Egypt and Mesopotamia. Blue, for instance, is linked with divine justice, the gods and protection in Egypt whereas turquoise is identified with life and rebirth (Duckworth 2011, 116; Jackson & Wager 120). While most Mycenaean glass beads are dark blue, light blue/turquoise beads tend to have faunal motifs, perhaps supporting the idea of light blue being associated with life (Worrall 2019, 40). Other examples include the rosette motif which has links with the Near Eastern Ishtar and as such, may be associated with protection (Hughes-Brock 2008, 131). As rosettes are predominantly dark blue/blue, this can link with the Egyptian association of blue with protection and divine justice (Duckworth 2011, 116). The use of imported Near Eastern motifs have been seen in star-disk pendants in the LH IIA period, again associated with Ishtar (Eder 2012, 224). However, it can be hard to tell if symbolic associations transferred between cultures and care should be taken (Hughes-Brock 2008, 131). The use of imagery and motifs would seem to imply that the choice of blue glass could be to do with



*Figure 3.1: Left, gold pendant associated with Ishtar **47.1a-h** (Getty Museum, n.d.) and Right, Mycenaean glass Rosette beads **1868,1025.57** (British Museum, n.d.)*

possible symbolic meanings attached to the colour blue. More practical alternatives have also been suggested for the predominance of blue as opaque reds, whites and yellows cannot be as easily re-melted without losing their colour due to their crystalline formations (Jackson & Wager 2011, 117). Hughes-Brock has also suggested that the lack of white may be due to the colour not contrasting well against the pale skin of women or that white may be associated with death and mourning (Hughes-Brock 1999, 285).

It has been suggested on numerous occasions that glass may be associated with funerary rights as they are commonly found in burial contexts (Jackson & Wager 2011, 116). Nikita associates dark blue beads with burial of the dead and Panagiotaki suggests that there is no evidence that glass was worn in life as the beads depicted in wall paintings could represent lapis lazuli (blue) or gold and carnelian (yellows and reds) (Nikita 2003, 33; Panagiotaki 2008, 52). However, it is also likely that the predominance of glass in burial contexts is due to survival bias (Jackson & Wager 2011, 116). The use of glass in architecture, furniture and as offerings in shrines may also suggest that glass should not be solely associated with death and burial. Another case against beads being considered as purely linked with funerary context is the case of the pectoral beads found on the Uluburun shipwreck which alongside pairs of other Mycenaean affects, suggests that two Mycenaeans were onboard (Bachhuber 2006, 352). This would suggest that glass beads were worn by the living and so should be seen beyond the funerary context. An association with protection and life/rebirth may explain any links with burials as this is a theme important to both the living and the dead.

3.1.1 Archaeology of Mycenaean Colour

Linguistic evidence for colour is relatively rare in Mycenaean Greece. The writing of the time is known as Linear B and is based around a set of phenograms that represents pure vowels or a consonant + vowel combination (Palaima 2012, 363). The language is a form of early Greek and was decoded in 1952 (Hughes-Brock 2003, 10). Words that have been directly linked with colour are *re-u-ko* (white), *me-ra* (black), *po-ni-ko-ro* (bright red), *ka-sa-to* (yellow), *ku-wa-no* (blue) and *er-ru-to-ro*

(another red) (Warburton 2016). Other terms have been identified and linked with colour such as *wo-no-qo-so*, translated as a descriptive term for cattle meaning 'wine coloured on its backside' (Blakolmer 2004, 63). Gillis proposes that linguistics may suggest that desaturation was important part of colour in Mycenaean Greece due to terms for pale/light cattle and plants, as well as colourless clothes (Gillis 2004, 58). It may be suggested that the Mycenaeans, like Homer and Hesiod, interacted with colour in an abstract way, i.e. the wine dark sea (Blakolmer 2004, 63). If this is the case, it may be suggested that colour could have been a synaesthetic experience. A synaesthetic approach has been suggested by Bradley for the Greek and Roman world based on their colour terminology (Bradley 2013, 133). The theory is that these terms bring more than just the abstract conception of colour, instead invoking the other senses; so the wine dark sea could bring up not just imagery of a sea at sunset but also the intoxication and dangers of wine (Bradley 2013, 133). Applying this to the Mycenaean period can be difficult due to the limited range in text. Some examples of terms used for cattle include the above-mentioned *wo-no-go-so*, *po-da-ko* ('quick/white legs') and *to-ma-ko* ('swift/white mouth') (Blakolmer 2004, 63). While this suggests that the later Greek language had connections between colour and abstract contacts, there is no certainty that this connection existed in Mycenaean Greece. *Po-da-ko* and *to-ma-ko*, seem to suggest a link with speed and white, drawing potential for colour evoking wider senses. However, the use of κύανος in the Homeric epics may provide more firm support for a synaesthetic experience. While κύανος is linked with dark blue glass in Mycenaean Greece, in the Homeric epic it covers colours from dark/black to blue and, as an adjective for objects that have been touched by the gods or the supernatural (Nightingale 2008, 80). It can be suggested that these associations could have been present during the Mycenaean period and this may support the idea of a synaesthetic approach (Nightingale 2008, 80). As ku-wa-no appears to be a loan word from the Hittites, potentially the associations of supernatural comes via attitudes towards glass rather than the colour.

Archaeology may provide further information on colour in the Mycenaean world. Colour plays an important role in wall frescoes and can also be seen in burial contexts. Painted plaster first

appears in the Neolithic period and becomes more widely used in the Bronze Age (Peters 2008, 192). From the late Neolithic, the Minoan palace of Phaistos has monochrome wall painting while Vassiliki, while from the EBA, Knossos and Myrtos begin to show evidence of wall painting (Peters 2008, 192). Wall paintings show various scenes for instance, the naval scenes such as Hall 64 from the Palace of Nestor (Pylos), while others have procession scenes which have been found at multiple locations (Brecoulaki et al. 2015, 260; Muskett 2007, 36). Figures depicted on wall paintings can give us an idea about the clothes (and their colours) that were worn by the Mycenaeans. The outfits are considered to be ceremonial, taking influence from the early Minoan outfits (Muskett 2007, 36). Bodices on women tend to be blue or red in colour with green and yellow being almost unheard of, the Mykenia being a rare example of a yellow bodice (Muskett 2004, 69). The lack of green may be because it is created by mixing yellow and blue, both in dying the cloth (which required double dyeing) and creating the pigment for wall paintings, (Muskett 2007, 44). However, some copper-based pigments were capable of producing green (Brecoulaki 2014, 12). In terms of wall pigmentation, the primary pigment for red, orange, yellow and pink is ochre, which contains a mixture of iron oxides (Perdikatsis 1997, 104). Azurite, Egyptian blue and iron rich riebeckite have been identified as pigments used for blue (Peters 2008, 201). White is coloured with calcite and black with carbon or magnesium oxide (Perdikatsis 1997, 104). Purple could be produced with murex, ranging from pink to mauve (Brecoulaki 2014, 9) While the use of azurite (copper ore) is used for blue, malachite – which is also found in the Aegean – is not used for green and other than one possible case of iron producing a green pigment, it appears that green is made solely by mixing blue and yellow (Peters 2008, 201). However, other copper green minerals have been identified such as 'pseudomalachite, chrysocolla, atacamite and paratacamite' has been found in Mycenaean Greece (Brecoulaki 2014, 10). The use of red/brown for male figures and white for female suggests that colour coding was used in Mycenaean wall painting and so choices in garment colour may likewise have been chosen to convey certain meanings (Muskett 2004, 68). The scarcity of green in wall paintings is also mirrored in funerary remains, although it is possible that green items would have

been perishable goods (such as fabric) and thus have not survived (Gillis 2015, 520). Brecoulaki notes that the low use of green in wall paintings is limited to special rooms within the palace, which may designate special use of a rare pigment (Brecoulaki 2014, 13). Burial evidence suggests that there may instead be an emphasis on shiny as opposed to matt objects and that lustre may be more important than colour; finds in burials to support this include the tinned vessels, which turned the matt ceramics of everyday use into a more reflective vessel (Gillis 2015, 520).

3.2 Frattesina and Italy

The Recent Bronze Age site of Frattesina is a prominent site in relation to glass production with archaeological evidence including crucibles with glass adhering to the sides (Biavati & Verità 1989, 296). It is located in the Po Valley (Northern Italy) and is part of the Terramare culture (Cardarelli 2009, 506). Terramare settlements were quadrangular and were surrounded by ditches, filled with water from diverted rivers (Cavazutti et al. 2019, 625). The culture fully emerged in the Middle Bronze Age 2 (c. 1550 – 1450 B.C.) when sites began to exceed 2 hectares (Cardarelli 2009, 449-451). Predominantly, settlements are found in the Emilia Romagna area where over 220 sites have been recognised (Saracino & Bellintani 2015, 77). It seems that the economy was primary cereal grains, sheep/goats and pigs, although extensive bronze finds also indicates the likelihood that most villages had a skilled smith (Cardarelli 2009, 452). The site of Frattesina has more intensive craft working and production than other sites in the Po Valley (Bellintani 2014, 112).

While the site of Frattesina is dated to the recent Bronze Age, the lowest context has not yet been reached (Saracino & Bellintani 2015, 80). The settlement, located on a paleochannel of the River Po, was 30-40 km from the Adriatic coast and was 20 hectares in size, split evenly between a core and periphery areas (Cavazutti et al. 2019, 626). It is the largest of the settlements along the river course and has extensive evidence for artisan work, including over 70 moulds for metal working (Towle et al. 2001, 10). Likewise, glass moulds have been found, with ingots which fit the mould (Henderson et al. 2015, 3). Frattesina had extensive trade networks, with ostrich shell and

Mycenaean pottery showing trade from the Mediterranean and amber from northern Europe (Bellintani 2014, 112). Part of the success of Frattesina may be in its location, on the crossroads of land, fluvial and maritime networks (Cavazutti et al. 2019, 626). Considering that there is evidence for the import of goods from the East, it is interesting that the Eastern HMG is not imported (Henderson 1988, 440). Faience is found from the Early Bronze age and by the Middle Bronze Age, a distinction is seen between a mixed alkali faience in the North (which has a comparable composition to the later Frattesina glass) and central Italian faience (which is a higher soda mixed alkali glass) (Angelini et al. 2005, 33).

4 METHODOLOGY

4.1 ELECTRON PROBE MICROANALYSIS

4.1.1 The Atom

An atom is composed of a central nucleus, containing the protons - which have a positive charge - and neutrons – which have no charge and orbiting electrons, which have a negative charge. Atoms are without an overall charge, as they possess an equal number of protons and electrons. The number of protons (the Atomic Number, *Z*) defines an element. For instance, Si has an atomic number of 14, meaning it has 14 protons and 14 electrons, see Figure 4.1: A Silicon Atom. The weight of the atom is defined by the number of protons and neutrons with the weight of the electrons being negligible. When an atom gains a charge by gaining or losing an electron, it becomes an ion, for example, Na_2O is composed of two positively charged sodium ions (1 Na^+) and one negatively charged oxygen ion (O^{2-}). The electrons in an atom exist in different shells

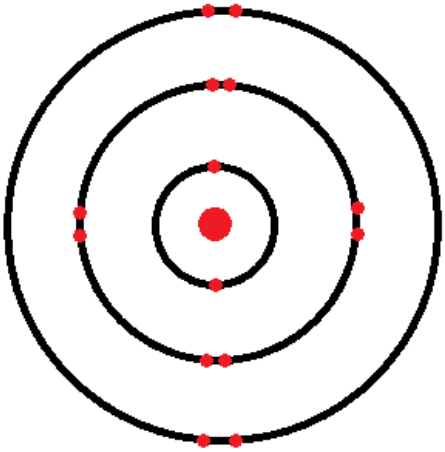


Figure 4.1: A Silicon Atom (drawn by author)

(or orbitals), with shells having different numbers of electrons. The most inner shell can have up to 2 electrons, the next shell 8, for example. Each shell has to be complete before a subsequent shell can be filled. If an electron is knocked out from its position in an inner shell, the atom will seek to return to a more stable configuration which occurs by the release of an Auger electron or characteristic X-Ray which is equal in energy to the difference in energy level (Lifshin 2001, 2566).

4.1.2 Light

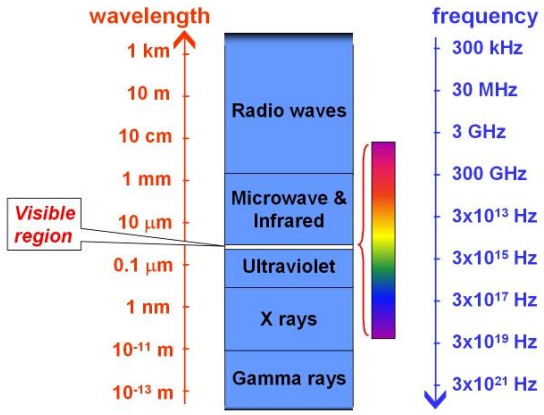


Figure 4.2 The Electromagnetic Spectrum (Swinburne University n.d.)

Light exists both as a wavelength and particle (a photon). Visible light is part of the Electromagnetic Spectrum and which has different divisions depending on wavelength or frequency. One of these categorises is the visible light, which has a wavelength between 700 and 400 nm while another of these categories is X-rays, which have shorter wavelengths and a higher frequency (Breithaupt 1987, 291). Visible light can be further subdivided into different colours, with purple and blue having shorter wavelengths and higher frequency than reds or oranges. The light we see is caused by the absorption of certain frequencies and the reflection of seen colours (Gow 2014, 804). The energy of a photon can be calculated from the frequency using E=hf, where E= energy, h = Planck's Constant and f= frequency (Duckworth 2011, 121). The frequency of a wave can be related to its wavelength (λ) by the use of $\lambda = \frac{v}{f}$ where v is the velocity of the wave, which in case of light is the constant c.

4.1.3 Electron Microprobe

The Electron Microprobe Analyser was invented in the 1950s by Castaing of the University of Paris (Lifshin 2001, 2565). Through it, high-quality analysis of silicates (including glasses) can be achieved

(Vaggelli et al. 1999, 297). In theory, all elements with an Atomic Number of 4 and above can be detected although in practice not all instruments will be capable of detecting lighter elements (Z<10) (Reed 1995, 49). The EMPA can measure minor and major and, in many cases, trace elements with an accuracy of up to ±1% for quantitative elemental analysis (Reed 2005, 3). Furthermore, it is a non-destructive technique that makes it ideal for analysis of rare materials – such as in cosmochemistry with meteorite or lunar samples (Reed 1995, 51). However, intense irradiation of a sample can modify or destroy a sample either by heating or local surface charging (Janssens 2013b, 130). In glasses, this causes 'alkali migration', especially of Na and preventative techniques include: decreasing the current of the beam, increasing the diameter of the beam, or moving the specimen continuously during analysis (Reed 1995, 80).

EMPA works by using a heated tungsten filament to produce an electron beam (Lifshin 2001, 2565). The electron beam excites an area of the sample, which can be as small as μm^3 (Vaggelli et al. 1999, 297). The majority of the electron beam is dissipated thermally but one in a thousand incident electrons will cause the ejection an electron from the core shell of an atom creating a vacancy which results in the emission of a characteristic X-Ray or Auger electron as the vacancy is filled by an outer shell electron (Lifshin 2001, 2565). The release of an X-Ray is called X-Ray fluorescence (Janssens 2013a, 82). As the transitions that X-Ray spectroscopy is principally interested in takes place in the inner shells, the information gained is at the atomic level rather than the molecular (Lifshin 2001, 2566). For the analysis of glass, results are given as weight percentages of oxides, which is the convention for the analysis of silicates (Reed 1995, 86). Most Electron Microprobes can perform both Wave Dispersive Spectroscopy (WDS) and Energy Dispersive Spectroscopy (EDS) analysis (Janssens 2013b, 130). Both WDS and EDS make use of X-Ray fluorescence to analyse a sample although each method has its own advantages and disadvantages.

WDS uses the wavelength of X-Rays emitted by the sample to gather compositional data. A crystal (of known interplanar spacing) is used to diffract the light so that a set wavelength will hit the detector (Janssens 2013a, 95). Crystals of different spacings are used to measure different elements

and an electron microprobe is often fitted with multiple crystals (Lifshen 2001, 2567). WDS can only detect one wavelength at a time, therefore multiple spectrometers and crystals are used to take multiple readings simultaneously (Reed 1995, 76). Using the Bragg equation nλ = 2d sinθ (where nλ is a whole wavelength or an integer multiple of; d is the distance between planes; and θ is the angle of incidence), it is possible to calculate the wavelength (λ) of the X-Rays (Semat & Albright 1939, 114 – 120). Moseley's law can then be used to associate the wavelength with a specific element (Lifshin 2001, 2567).

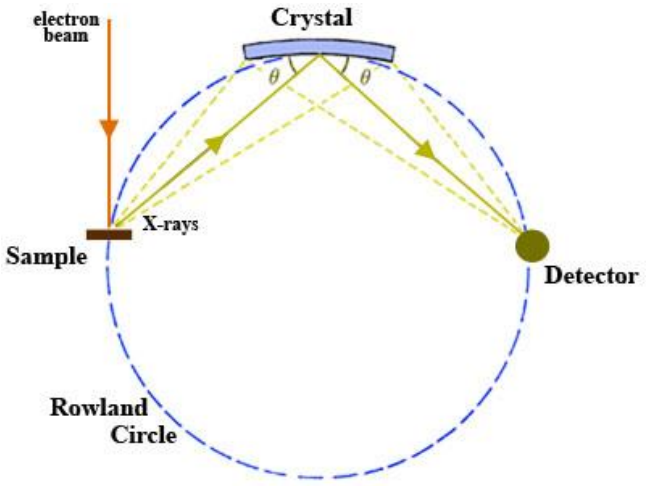


Figure 4.4: WDS (Darrel & Goodge 2016)

Moseley's Law: $$f = \frac{c}{\lambda} = a(Z^2 - \sigma^2)\left[\frac{1}{{n_2}^2} - \frac{1}{{n_1}^2}\right]$$

Where a and σ are constants and n is the energy level number (Duckworth 2011, 123)

In this way, the WDS can perform qualitative analysis of a sample while measuring the line intensity of the sample and a standard can be used to provide quantitative analysis (Reed 1995, 49).

Energy dispersive Spectroscopy (EDS) was invented in the 1960s and while it has poorer resolution leading to lower quality peak to background ratios and peak overlap, its speed and convenience has led to it being widely accepted on electron beam instruments (Lifshin 2001, 2568). EDS tends to be used for qualitative analysis due to the speed of which it can obtain an analysis of the whole spectrum (Reed 1995, 73). As is indicated in the name, EDS measures the energy of the X-Rays in order to identify the composition of a sample with the rate of detection used to provide quantitative data (Bergström 2015, 102). EDS can be useful when paired with WDS as the quick analysis of the whole spectrum allows for rapid qualitative analysis of a sample in order to identify any unexpected inclusions. This is useful as WDS requires input for the detectors and is a slower

process, so it is beneficial to measure only those elements required. Glass analysis typical measures Na_2O, FeO, Cl, PbO, F, CoO, P_2O_5, TiO_2, SiO_2, NiO, BaO, SO_3, MgO, CuO, SnO_2, K_2O, Al_2O_3, ZnO, MnO, Sb2O5, As_2O_5, Cr_2O_3 and CaO.

For EMPA analysis, the samples have to be able to be able to survive in a vacuum as gas atoms can scatter the electron beam, so a pressure of lower than 10^{-4} mbar is used (Reed 1995, 69). Only a small sample is required, which can be as small as 0.5mm in length, as the analysis covers an area of only a few µm or less (Lifshin 2001, 2565; Nikita et al. 2006, 39). Samples are then mounted in epoxy resin and ground to present a flat surface, which also removes any weathering that may have occurred. As glass is nonconductive, a layer of carbon coating (usually around 20nm thick) needs to be applied to provide a path for the incident electrons (Reed 1995, 51). Typically, three to five spots will be analysed on a sample and an average taken (Henderson 2000, 17). The Standard used when analysing Bronze Age Glass is Corning B, which is one of 4 standards created by Corning in order to have a universal high-quality standard allowing analysis from across the globe to be compared (Vicenzi et al. 2002, 720). Typically for glass, a defocused electron beam of c. 80 µm is used to avoid loss of alkali (Henderson 2000, 17).

4.2 Methodology of Colour in Archaeology

Colour plays a significant role in everyday life, being part of our observed world but also providing a social role, with evidence that colour can effect mood (as seen in the use of Baker-Miller pink in prisons) and also be used as a signifier of identity (Rose-Greenland 2014, 81). The meaning of colour changes depending on society with one such example being the varying use of black or white during funerals (Gillis 2004, 56). As colour can be considered subjective, this can make it a difficult subject to understand and study. Different disciplines have different approaches to colour; psychologists tend to look at how colour is perceived, philosophers on the fixity of colour while archaeologists look at colour in relation to social theory (Rose-Greenland 2014, 83). There are many factors that might be used to examine how a culture interacts with colour. One method is to look at the acquisition of

colour and production, to what extents were people willing to go to acquire colour. Another way is to look at linguistic evidence, which has been mentioned in Section 3.1.1, as this can show how people express colour. Further techniques include ethnographic comparisons with modern and historical cultures as well as psychological studies which investigate whether reactions to colour may have biological roots as well as cultural.

4.2.1 Acquiring Colour

The earliest evidence for pigment use comes from Kathu Pan (North Africa) and dates to c. 500 000 B.P. (Montsiou 2019, 58). Early colour use is predominantly black (obsidian), white (shells) and red (ochre) which are used through the Palaeolithic (Warburton 2019, 30). Yellow and brown ochre use is also seen but less commonly than red ochre although this could be due to bias in preservation as heating changes the colour (Montsiou 2019, 58). Preservation bias has also been suggested for the absence of certain colours, for example green in Mycenaean burials, as such colours may have been on perishable materials (Gillis 2015, 520). It is noted by Warburton that blue and green gain more significance in art as cities emerge, possibly influenced by their predominance in the natural world and absence in settlements (Warburton 2019, 13). This may suggest that the use and acquisition of colour is influenced by rarity of said colour in the environment around a people.

One way to judge the importance of colour is through tracing the source of the colour. For example, it has been found that shells have a travel distance of up to a few hundred kilometres during the Palaeolithic (Montsiou 2019, 60). This may suggest that white was an importance colour although it should be noted that colour cannot be divorced from its source material. A greater significance may be the shell itself. Other materials that had large travel distances include rock crystal and obsidian, which have ulterior functions (stone tools) as well as having colour and lustre (Montsiou 2019, 60). A similar case can be seen in Neolithic Stone Axes from Great Britain which were quarried from difficult to access sites (such as Scarfell, Cumbria) which would have made poor tools but were recognisable by colour (Duckworth 2011, 66). In this case, the difficulty of accessing

colour may have increased its worth. The expense and difficulty to acquire colour has continued to be important, with a later example from the 15th century emphasis on expensive paint, clearly seen in the specification of ultramarine blue and its grade (ultramarine was the third most expensive paint after gold and silver) (Rose-Greenland 2016, 83). This can be applied to colour found in the Bronze Age, with the provenance of the material potentially indicating worth.

4.2.2 The Language of Colour

An influential, although now widely discredited, study by Berlin and Kay set out a progression of colour language evolution which starts with black/dark and white/light (Stage I) before adding red (Stage II), 'grue' (a form of green and blue) and yellow appear during Stages III and Stage IV while Stage V distinguishes between blue and green (Bradley 2013, 130; Duckworth 2011, 61). This matches somewhat with the use of colour, with the earliest evidence being black, white and red. It is of note that later colours such as blue and yellow enter the vocabulary as materials, i.e. lapis lazuli or gold and leave a greater impact on the linguistic vocabulary (Warburton 2019, 30). An inversion of this type of colour terminology occurs during the medieval period where purple could be used to denote the quality of the silk rather than its colour (Duckworth 2011, 61). In this way, colour can be considered to be more than just an abstract concept and be bound with materiality. Faience may present a further case as the Ancient Egyptian term '*tjehnet*' means bright/scintillating which are words used to describe the sky and as faience and turquoise was offered to Hathor, 'The Lady of the Sky', it might be inferred that they may be seen as physical manifestations of the sky (Nicholson 2012, 12). Considering colour as an aspect of material can link to the synaesthetic approach suggested by Bradley (2013). Here, it can be considered use of words such as '*oinops*' invokes not just the colour of wine but also its flavour and effects (Bradley 2013, 131). In essence, colour can be considered irrevocably tied with the material property from which it derives. Brecoulaki, however, suggests that these terms should be considered descriptive, with multiple purple/red colour terms being used – not just *oinops* (Brecoulaki 2014, 12). While such calling items 'sky coloured' or calling

the sea ‘wine dark’ invoking the dangers of wine might seem a somewhat alien concept, it can be seen in modern English (Bradley 2013, 131; Gillis 2004, 59) Golden locks might be used to describe a dazzling blond and new recruits might be described as ‘green’, similar to fresh foliage. The use of language, while interesting, may not be practical for the interpretation of colour and may be better used in relation to other methods.

4.2.3 Ethnographic studies of Colour

As we cannot question past societies on their views and interactions with colour, ethnographic studies and analogy play important roles in understanding the role of colour in past societies. For instance, studying the use of the Ancient Greek κύανος and other colour terms in relation to the Mycenaean interaction with colour can be considered a form of ethnographic analogy. Other examples include Moutsiou comparisons between the South African Faure Smith industry where a sparkly form of hematite (specularite) was gathered with a maximum transference distance of 10-170km and the Australian Aboriginals who make specific journeys to obtain a special ochre (‘…brilliant, shimmering, deep violet-hued red’) from the Pukardu Hill (Moutsiou 2019, 62). Ethnographic analogy is a useful tool and it has been argued that it has been used for the interpretation of artefacts since the beginnings of archaeology (Peregrine 1996, 317). There has been a growing mistrust of analogy as it can distort or limit interpretations, being primarily a subjective method (Wylie 1985, 68 & 77). The principle behind Ethnographic Analogy is that non-observed behaviours can be explained by observed behaviours, thus creating an analogy (Ascher 1961, 317). Some have suggested that prehistoric archaeology could not exist without analogy, for example the interpretation of Stone Age ‘arrow-heads’ uses analogy, drawing comparison with later metal arrow-heads (Could 1971, 143; Mason & Thompson 1972, 8). Caution must be taken when using analogy as they can be inappropriate, considering analogies often make use of modern societies which can be removed by time and space from that which they are being compared with (Peregrine 1996, 316). A suggestion is that analogies should therefore be created out of multiple and

relevant case studies (Shelley 1999, 581). Relevance may be denoted as being a comparison with people under similar ecological regions or constraints or having similar technological levels (Ascher 1961, 319). Others have suggested that using the local folk history of an area may be of more relevance (Wiley 1985, 70). It has been argued that if something can be observed across multiple cultures, then it is likely universal to humankind and therefore would have also existed in past societies and can be applied to archaeology (Peregrine 1996, 320). Analogy can be a useful tool, although caution is needed, and the analogy should be intensely evaluated in order to identify its relevance.

4.2.4 Psychological interactions with Colour

While Ethnographic analogy has fallen out of favour due to its lack of scientific adequacy and inability to quantify its accuracy, psychological investigations into humanity's innate interactions with colour can provide a similar role (Morwood 1975, 111). Studies are carried out on modern populations, using scientific methods to study human behaviour. Importantly, these studies can help to distinguish between whether behaviours are innate to humankind or are influenced by the culture that the people were raised in. Identifying whether certain behaviours are genetic or environmental can be useful for understanding how people interact with the world and colour. There have been studies, for instance, into how language can affect colour perception. This question has had a long history and is key in the debate for how language affects thought (Winawer et al. 2007, 7780). It has been well observed that distinct cultures make various differentiations between colour categories, such as the two Russian words that correspond to blue (light) and blue (dark) (Bradley 2013, 129). A study carried out on English and Russian speakers showed that Russian speakers had an advantage for distinguishing between shades of blue and the influence of language became even more apparent for near colour comparisons (Winawer et al. 2007, 7782). The conclusion was that while English speakers can distinguish between light and dark, Russians cannot avoid distinguishing them (Winawer et al. 2007, 7783). Another study carried out by Ou, Woodcock and Wright looked at

colour emotion (i.e. what emotions colours evoke) between Chinese and British groups (2004). The study concluded that colour emotions are 'culture-independent' for their test groups (Ou et al. 2004, 240). The use of psychology in regards to colour in archaeology may prove to be of greater use, offering a scientific study into humankind's innate relationship with the world around them. Studies such as those by Ou et al. may suggest that an archaeological and linguistic approach may be needed to understand the specific relationship Bronze Age cultures had with certain colours. Meanwhile the study on Russian blue by Winawer may help in understanding where boundaries may exist between shades.

5 META-ANALYSIS AND DISCUSSION

This study presents a meta-analysis of published data from:

- Brill (1999) – glass from the Uluburun
- Degryse et al. (2010)
- Henderson, Evans and Nikita (2009)
- Jackson and Nicholson (2010)
- Karantzali (2001)
- Karatasios and Triantafyllidis (2012)
- Kempt et al. (2020)
- Nikita and Henderson (2006)
- Shortland and Eremin (2006)
- Shortland et al. (2018)
- Smirniou and Rehren (2011)
- Walton et al. (2009)
- Zacharias et al. (2018)

As well as this, unpublished data from Professor Julian Henderson of the University of Nottingham was used. This data is composed of 43 samples of various glass from Frattesina (including ingots, raw glass, beads and decoration) and can be found in the Appendix, Table A. As discussed in Section 4.1.3, samples were mounted in an epoxy resin and carbon coated. The analysis was carried out on a Cambridge Microscan 9 Electron Microprobe at the Research Laboratory for Archaeology and the History of Art (Oxford University).

For the purpose of this discussion, the colour blue has been sorted into three shades, based on composition. These three categories use Shortland and Eremin's division of copper blue (above 0.1 wt% CuO), cobalt blue (above 0.05 wt% CoO) and finally copper cobalt, which has both of the above (Shortland & Eremin 2006, 591). The decision to divide blue based on composition was taken as copper based glasses are capable of producing dark blue, which should not be confused with the dark blue produced using cobalt, which is generally linked with an Egyptian production. A similar approach can also be taken with other colours, such as green, which can be produced with either iron or a mixture of antimony, lead and copper, which produces an opaque glass (Duckworth 2011, 51). As this work focuses on the colour blue (being the predominant colour in Bronze Age glass assemblages), blue is the only colour that has been subdivided. When pertinent, discrimination between the colourants is mentioned in text.

This meta-analysis includes 209 Egyptian analyses, 172 Mesopotamian (37 of these were found at Gurob, Egypt) but have been identified as having a Mesopotamian origin (Kempt et al. 2020), 141 analyses from Mycenaean Greece and 43 from Frattesina, Italy. With Elateia providing a total of 18 mixed alkali glass, this gives a total of 61 LMHK glasses and 504 HMGs. The benefit of meta-analysis is the ability to compose huge data-sets which may identify trends that might not be found on a smaller scale. Section 5.1.1 looks at biplots of principle elements, with a particular focus on potash and magnesia. Bi-plots are frequently used in glass analysis, being easy to produce, and an efficient and visual method to show the relationship between two elements. The use of R^2 allows a measurement of correlation. R^2 gives a measurement to represent the variation in one axis that can

be explained by the variation in the other. A higher value shows stronger correlation. While this can be heavily influenced by extreme points (giving a much stronger value), it is useful in regard to understanding how well points fit a trend. It is the square of r (also known as Pearson's Coefficient or the Coefficient of Correlation) which can likewise be used to measure correlation. Following from this, Section 5.1.2 uses the ratio of Ca:Al and Na:Mg to further explore the relationship between these elements in Bronze Age glass. This is presented using both bi-plots and tables. Section 5.1.3 makes use of Principal Components Analysis (PCA). This process condenses a wide array of parameters into a few components, in this case three. This process can help to identify correlations between parameters based on their proximity on the graph. The use of the Cal:Al against Na:Mg proves to be more effective for HMG, revealing higher ratios of Na:Mg in Mycenaean glass compared to Egyptian and Mesopotamian. Meanwhile PCA provides clearer results for the mixed alkali glass, presenting two potential groups.

5.1 The Chemical Components of Glass

5.1.1 Potassium, Magnesium and Cobalt Blue glass

An easy and visual way to show the difference between HMG, LMG and LMHK glass is through a graph plotting the wt% potash and magnesia. As can be seen in Figure 5.1, the groups can be clearly identified, although with some overlap. A fourth group can be recognized above the LMHK category which is potash glass. A few samples from Frattesina fit within this category, although the cut-off point between LMHK and potash glass is not clear. Likewise, there are a few glasses from Frattesina with low potash, comparable to some of the higher potash plant ash glass. There are also some three LMGs. Curiously, these are three samples from Egypt which fit firmly within the natron glass category. These are two samples from BM5 (white and copper-cobalt) and BM3 (white), which are from the Valley of the Kings and date to the 15th to early 14th century B.C. (Shortland & Eremin 2006, 602). There are other samples that come from this context but they sort within the HMG composition. The higher potash average for Mesopotamian glass can be identified, with few samples having less than 2.0 wt% K_2O. This contrasts with Egypt and Mycenaean Greece. The Mycenaean

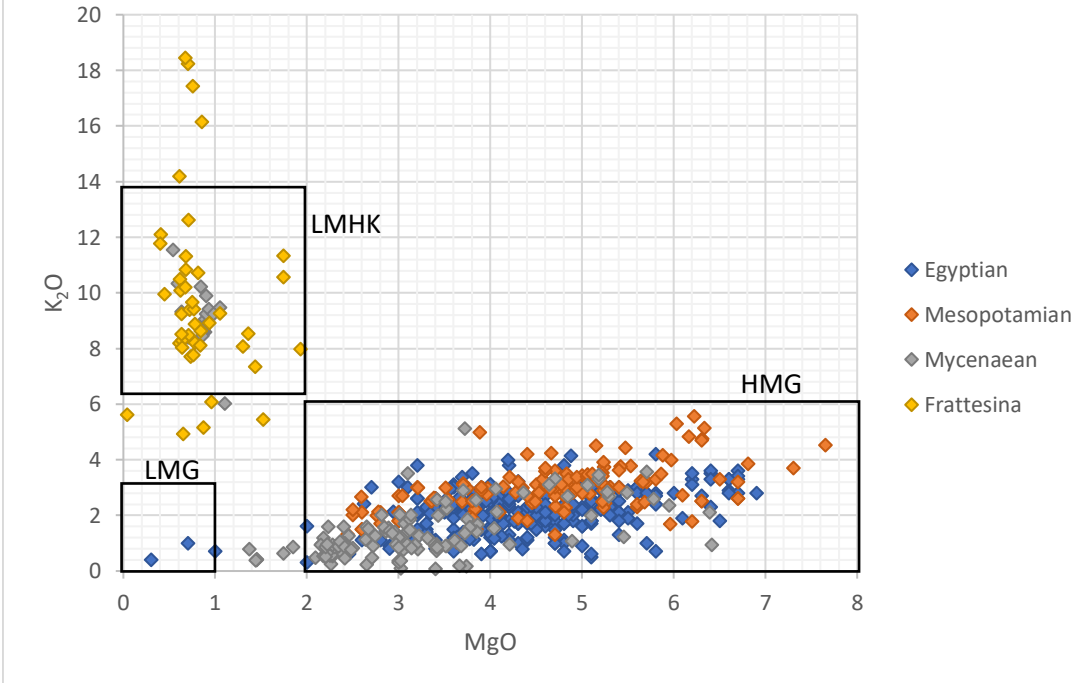


Figure 5.1: The division of different glass types using Potash against Magnesia

glass tends to have lower potash (<2.5 wt%) and magnesia (2-4 wt%) content than Mesopotamia and Egypt. Egyptian glass tends to span the ranges seen in both groups.

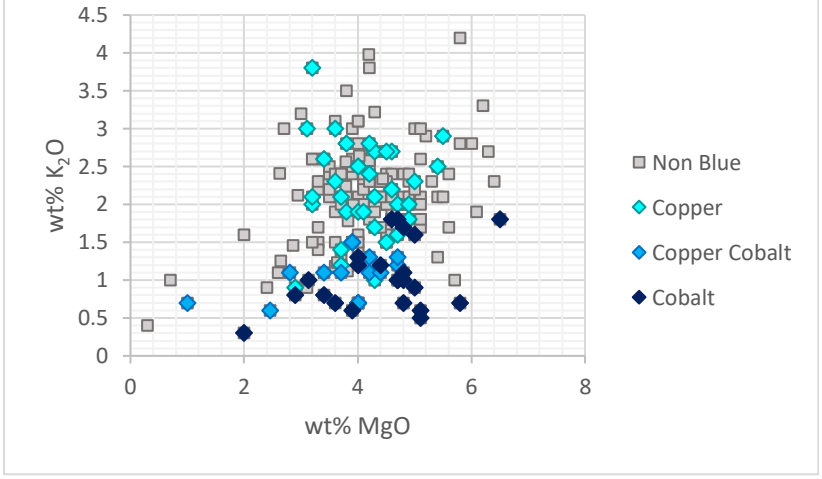


Figure 5.2: Potash against magnesia in Egyptian glass, with a focus on blue glass

The majority of the Egyptian glass with low potash is cobalt or copper-cobalt blue, which can be seen in Figure 5.2. This has been previously identified, with various different explanations put forward. One argument has been that cobalt blue glass was produced with natron, with magnesia introduced as an impurity of the cobalt (Shortland & Tite 2000, 147). It has been suggested that this implies cobalt blue glass was either the sole glass produced in Egypt, or other colours were produced with imported Mesopotamian glassworkers (Rehren 2001, 485). The use of bronze as a copper colourant has been linked with Egyptian production, in contrast with Mesopotamia's use of a purer source of copper which suggests local Egyptian production of non-cobalt glass (Kemp et al. 2016, 168). Furthermore, as natron took over from plant ash in later centuries, there has been question as to why, if natron glass was produced in the fourteenth century B.C., it did not become widespread (Rehren 2001, 486). An amended suggestion is that the cobalt blue glass may have been made from a mix of plant ash and natron, which would explain the lower levels of potash and magnesia (Wood & Hsu 2019). However, if this were the case, a mixing line would be expected between LMG and the lower magnesia HMG (Shortland & Tite 2000, 146). The three LMG Egyptian samples and a small collection of low magnesium Mycenaean glasses may represent a mixing line but are too few to be certain. It instead might be suggested that a low potash plant ash was used by a production site that happened to have a monopoly on blue glass, thus explaining the predominance of blue but not to the complete

exclusion of other colours (Rehren 2001, 488). Lately, it has been forwarded that natron and silica may have been used in the processing of a cobalt rich silver ore, producing a blue frit (Hsu & Wood 2019). This is similar to the suggestion that a cobalt concentrate may have been used, which was first proposed in relation to a pigment found on ceramic in 1981 and was later adopted in relation to glass production (Rehren 2001, 485). Like Egyptian glass, Mycenaean glass has lower levels of potash in cobalt blue glasses (as seen in Figure 5.3), but also has lower levels of magnesia. Furthermore, the lower potash includes a significant number of copper glasses (and purple), in comparison to the Egyptian. The lower levels of magnesia have been tentatively suggested as the use of a magnesium rich natron (Zacharias et al. 2018, 408).

In general, there does appear to be some level of correlation between magnesium and potash in cobalt blue glasses. This correlation does appear to be steeper in Mycenaean glass, and may also exist in glass of other colours. The R^2 value for potassium and magnesium in Mycenaean glass is 0.39, which suggests that the two elements are not highly correlated. This does not mean that there is no correlation – seasonal variation in plant ash (or plants) may vary, causing change in the composition and thus blur the correlation. It is curious that the cobalt blue glass in Figure 5.3 has a similar pattern to the plot of *Salsola* seen in Barkoudah and Henderson, FIG. 7. (2006, 316). While the Mycenaean glass has much lower potash, the two groups at roughly 2 wt% and 4% MgO (with the latter having higher potash) is similar to the ash. This may support the use of plant ash. Figure 5.4 looks solely at the cobalt blue glass from Egypt, the Uluburun and Mycenaean Greece, sorted by

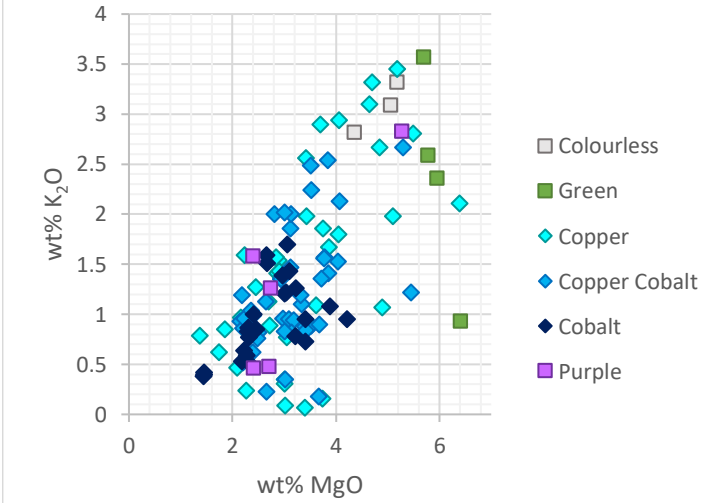


Figure 5.3: Potash against Magnesia in Mycenaean glass, sorted by colour

location. The majority of the cobalt glasses come from two studies, Nikita and Henderson (2006) and Shortland and Eremin (2006). The Mycenaean groupings may be representative of different production batches or variation in plant ash use. The Egyptian glass likewise shows a similar pattern, although the magnesia levels are higher than those of the ash used in the study. While the Mycenaean glass shows a more linear increase of potash with little variation of magnesia in these

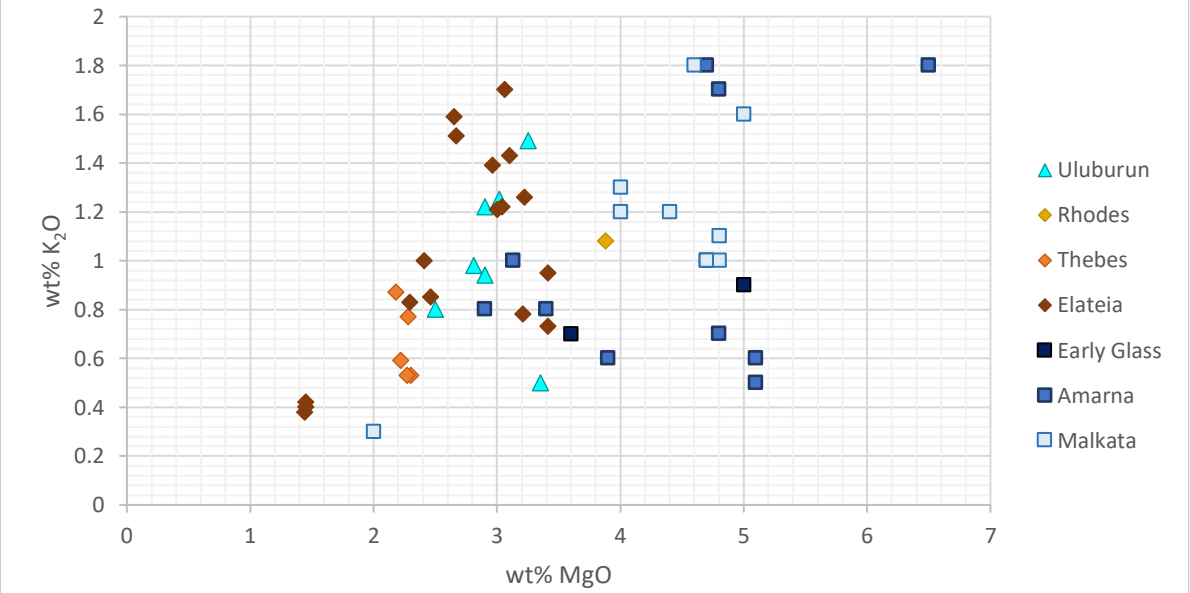


Figure 5.4: Potash against Magnesia in cobalt blue glass, sorted by location

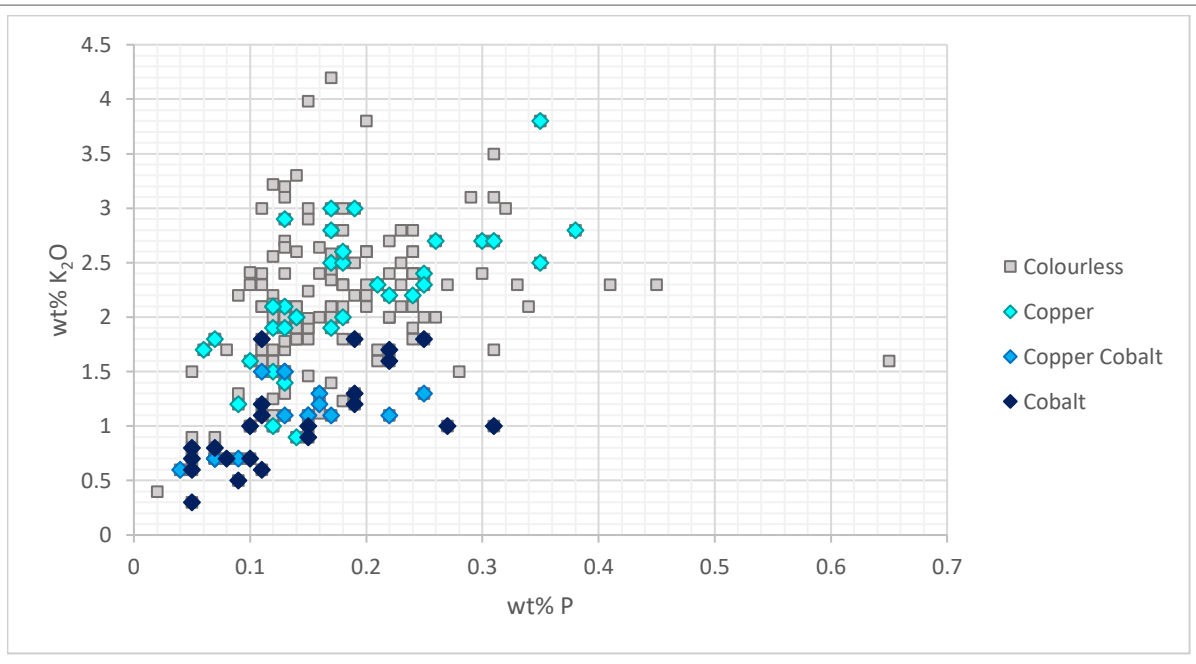


Figure 5.5: Potash against phosphorus in Egyptian glass

groups, the Egyptian glass potentially shows an inverse relationship in individual groups between potash and magnesia. These trends are not seen in copper-cobalt glass. A further association in plant ash is between potassium and phosphorus, as seen in Figure 5.5. Again this is seen in cobalt blue glass but not in glass of other colours. This is also seen in Mycenaean cobalt glass, following the same trend as Egypt. The overall R^2 value is low (0.38), likely influenced by the two high phosphorus cobalt glasses. If the visual correlation can be taken, this gives further credence to the use of a plant ash for cobalt blue glass.

Plant ash includes potash, magnesia, soda and lime. Figures 5.6 to 5.7 look at the relationship between magnesia, lime and soda. The particularly distinct low magnesia glass group is from Elateia and are LMHK glass (Nikita & Henderson 2006, 81). Mixed alkali glasses show a strong relationship between calcium and magnesium. This does not appear to exist in the Mycenaean or Egyptian glasses, which respectively have a Pearson's value of 0.26 and 0.16. Curiously, the Pearson's value for the Mesopotamian glass is -0.41. While these values are low – indicating no correlation – it is interesting that the Mesopotamian glass appears to have a vague negative trend. This may be linked with the use of a different plant ash, as has been suggested because of the higher potash in Mesopotamian glass. Little variation can be seen in soda between the glasses. This may

suggest that soda levels in plant ash remained fairly consistent while magnesia, potash and calcium varied.

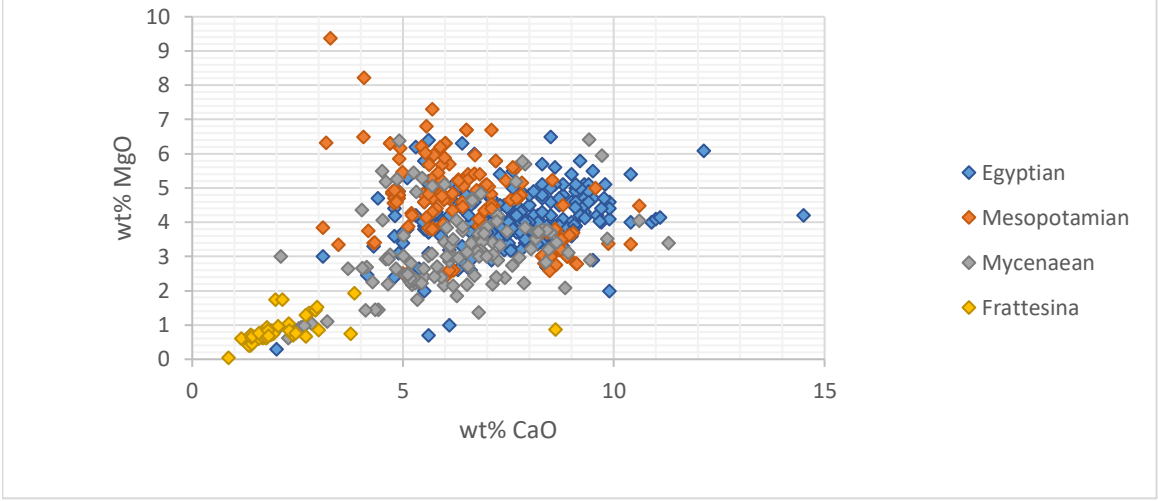


Figure 5.6.1: Magnesium against calcium in Bronze Age Glass

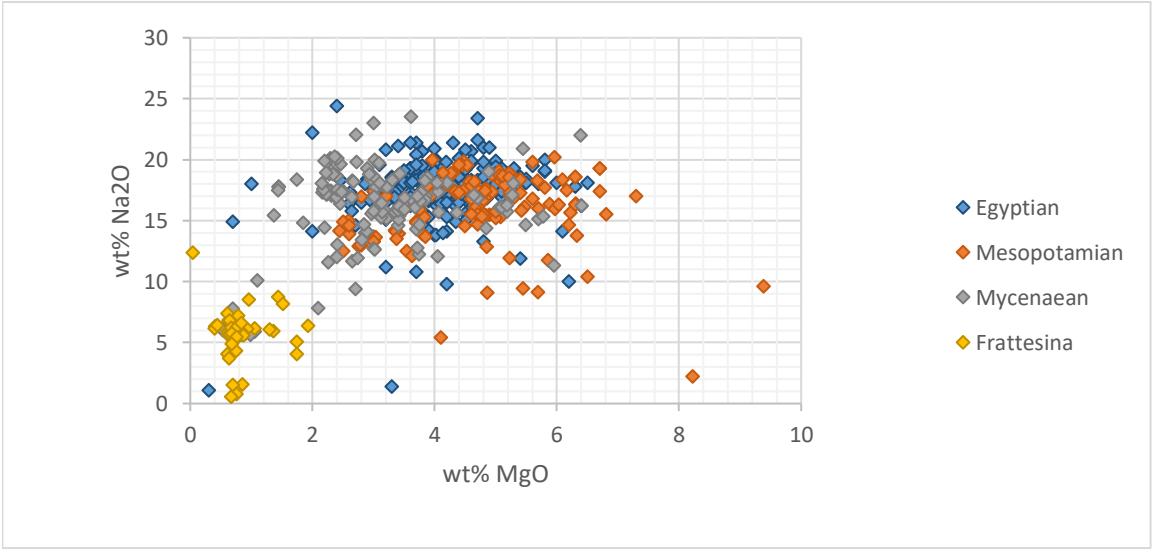


Figure 5.6.2: Sodium against Magnesium in Bronze Age Glass.

Figure 5.7, shows that although overall, there is very little correlation between these two elements, potentially there are two different groups of cobalt blue glass. One group is predominantly Mycenaean cobalt glass, as well as the glass from the Uluburun (which includes multiple shades of blue and one purple glass). A second group can be seen for Egyptian glass with the calcium wt% varying while magnesium has a fairly set level of around 5 wt%. The r^2 value for the cobalt blue Mycenaean glass is 0.60 while the value for the Uluburun is 0.61 – excluding the one

point with low calcium high magnesium. If the cobalt glass that follows the trend is considered for all three locations, this gives an r^2 value of 0.83 which would suggest a strong correlation; however, this is based on visual discrimination to identify two potential overlapping groups. It includes 88% of the Mycenaean cobalt glasses, 32% of the Egyptian and all of the cobalt Uluburun glasses. This may suggest that there are two different sites producing cobalt blue glass, with one type being predominantly shipped to Mycenaean Greece. Curiously, some of the glasses that do not fit the trend could be seen to have a similar gradient, but with higher magnesia. The equation for the cobalt glasses that follow the trendline is y=0.41+0.11, which would suggest if calcium and magnesium entered the glass together, there were little lime or magnesia impurities. The second potential trend, following a similar gradient has higher magnesia, perhaps suggesting an additional magnesia source.

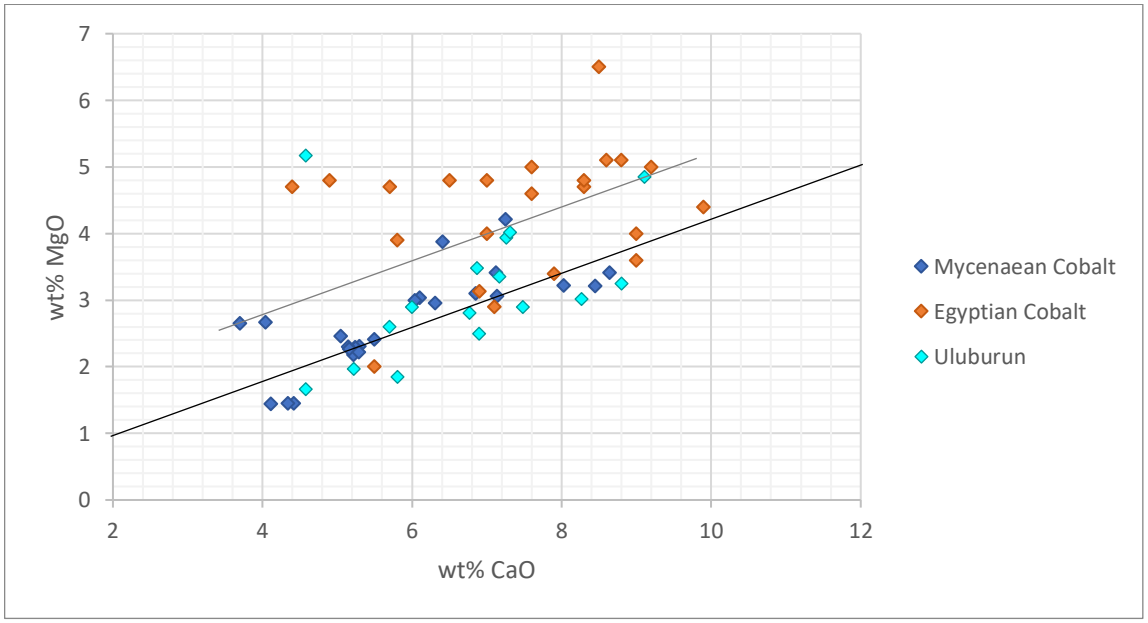


Figure 5.7: Magnesia against lime for glass from the Uluburun and cobalt blue Egyptian and Mycenaean glass.

A correlation between calcium and magnesium may suggest the use of dolomite or the use of plant ash grown on dolomitic soil, as proposed by Barkoudah and Henderson (2006, 313). If plant ash is the cause of this potential trend, the two trends may be caused by seasonal variation, geological location or other factors that may affect the composition. It could also be that a second

component has increased the magnesia. A further explanation may be that this represents a mixing line between two different compositions. It is also still possible that this may be coincidence as the trends are not particularly strong. Figure 5.8 focuses on cobalt and mixed alkali glasses, which have been noted for their correlation between calcium and magnesium. It can be seen that the HMGs have a looser correlation than the LMHK glasses. However, in contrast to Figure 5.6.1, the cobalt blue glass appears to have a stronger correlation than the overall composition of HMGs. Curiously, the cobalt blue Egyptian glass that has around 5 wt% magnesia fits along the same trend seen in the copper cobalt glass found at Nippur. Table 5.1 looks at the R^2 values for lime against magnesia as well as the ratio between the two elements. Two results have been given for the Mycenaean copper cobalt and Uluburun glasses as the samples circled in red in Figure 5.8 show clear variation from the bulk of the samples. The values for Frattesina exclude four potash glasses (Frat 14, 16, 19 and 20a) as well as two red glasses with high magnesia (1.74 wt%) and high alumina (an average of 6.70 wt% compared to 2.18) and can be considered compositionally different to the bulk of the glass from Frattesina. For the purpose of Table 5.1, these and the one high calcium glass from Frattesina (FRAT

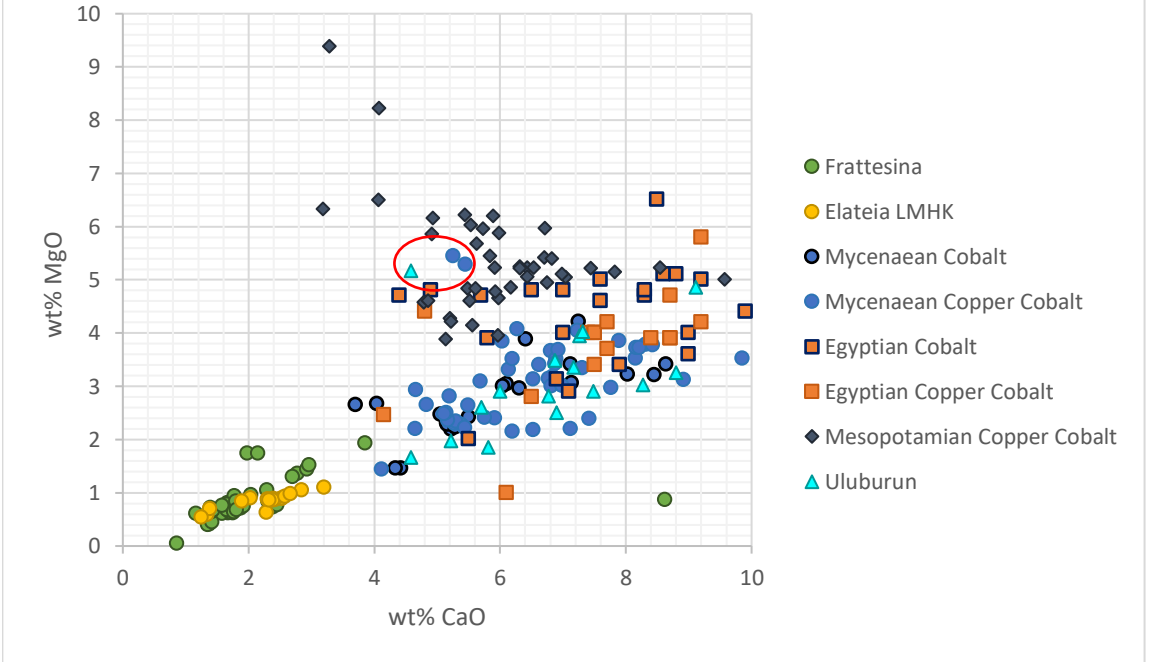


Figure 5.8: Calcium against magnesium in cobalt blue high magnesium glasses as well as glass from Frattesina, the Uluburun and LMHK glass from Elateia.

58b) have not been included. This is a white bead and the excess calcium may be due to the colour. The LMHK glasses have a stronger correlation and a slightly higher ratio than the HMGs. The cobalt Mycenaean glass and the glass from the Uluburun have a reasonable R^2 value and a similar, but slightly lower ratio of calcium to magnesium. Curiously, the glass from the Uluburun show a decent correlation across different colour types (5 turquoise, 2 copper cobalt, 5 cobalt and 1 purple). This contrasts with non-cobalt Egyptian and Mycenaean glass, where they do not show a strong correlation. This might be because the non-cobalt glasses may have multiple compositions or because calcium and magnesium are not correlated in these glasses.

	r^2	Ca/Mg	Count	Average Ca	Average Mg
Frattesina	0.85	2.36	36	1.88	0.80
Elateia LMHK	0.77	2.66	18	2.26	0.85
Mycenaean Cobalt	0.60	2.22	24	5.82	2.63
Mycenaean Copper Cobalt	0.10/*0.34*	2.07/*2.15*	48/*46*	6.49/*6.54*	3.14/*3.04*
Egyptian Cobalt	0.06	1.70	22	7.43	4.36
Egyptian Copper Cobalt	0.33	1.98	17	7.49	3.79
Mesopotamian Copper Cobalt	0.16	1.10	42	5.91	5.37
Uluburun	0.13/*0.61*	2.15/*2.29*	16/15	6.74/*6.88*	3.14/*3.01*

Table 5.1: The relationship between calcium and magnesium in cobalt glass from Frattesina, Mycenaean Greece and Egypt.

The LMHK glasses show a strong correlation between calcium and magnesium, as well as a strong correlation with aluminium and iron (Angelini et al. 2004, 1179). One suggestion for the relationship between calcium and magnesium in glass from Frattesina is the use of a dolomitic source of limestone (Henderson et al. 2015, 2). These elements can all be associated with impurities in the silica source, potentially explaining the strong relationship between them. However, isotopic analysis has suggested that the lime source for mixed alkali glass was from a radiologically older source than pure limestone (Henderson et al. 2015, 6). Studies of plant ash glass have shown that plant ash can produce correlation between magnesium and calcium, depending on the soil that the plant grew on – which is also seen in other soil associated minerals, such as aluminium and iron (Barkoudah & Henderson 2006, 313). This may suggest that the Ca, Mg, Fe and Al content of the glass from Frattesina are all derived from plant ash, reflecting the local soils. Figure 5.9 shows the relationship between aluminium and magnesium in Mycenaean and Egyptian glass. Cobalt coloured glasses have higher levels of alumina than the bulk of the Egyptian glass. This is commonly accepted to be caused by aluminium being an impurity in the cobalt source, although it has also been suggested that this may not hold as there are non-cobalt glasses that also have elevated alumina (Wood & Hsu 2019). Both the Egyptian and the Mycenaean glass can be seen to have plenty of non-cobalt glass with elevated alumina. The HMGs do not appear to have any correlation between

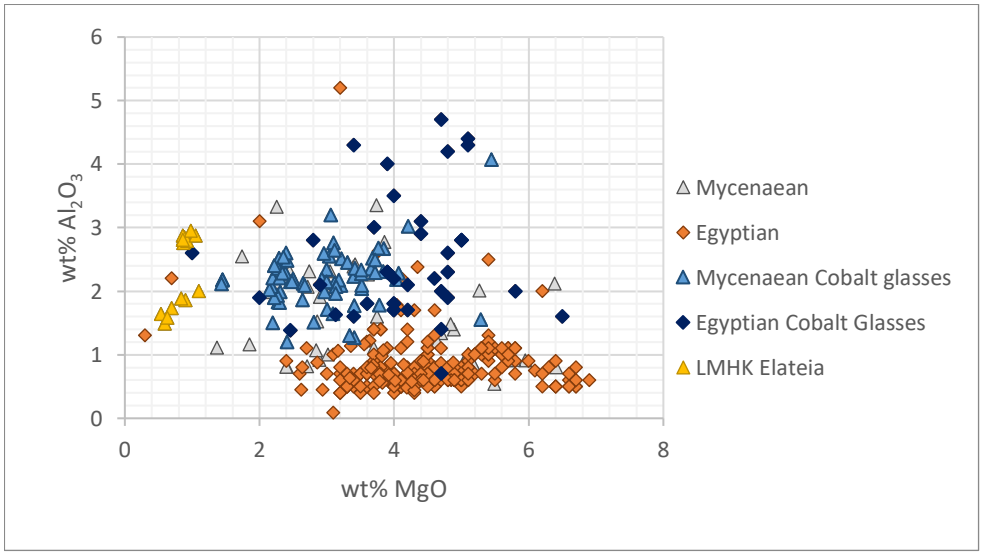


Figure 5.9: Aluminium against magnesium in Egyptian and Mycenaean glass

magnesium and aluminium, suggesting a different magnesium source for them in contrast to the LMHK glass. The mixed alkali glass from Elateia plots separately and in two groups. The higher alumina group forms a tight cluster while the lower alumina group shows correlation between alumina and magnesia, as is seen in glass from Frattesina. Curiously some Egyptian and Mycenaean glasses fit closely. One of these is BM3 (white), which is an early glass from Tomb of Amenhotep, and also has low potash. The Mycenaean samples are Ela/15, Ela/16 & Ela/18. These three glasses all have high levels of silica (around 74 wt%) and low levels of calcium, magnesia and potash compared to bulk of the Mycenaean glass. While these glasses appear to fit within the trend of the mixed alkali glasses from Elateia, they have low potash and so are clearly compositionally different. It is likely that this is coincidence.

A further and interesting point to note is that despite the strong overall trend between calcium and magnesium from the glass from Frattesina, this is primarily cobalt glass, as can be seen in Figure 5.10. While the red glass only has four points, this gives a strong R^2 value of 0.82 as the two red glasses that sit with the bulk of the glass fit on the trend towards the high alumina red two. The potash glass is composed of two blue samples, one green and an amber piece. The bulk of the glass plots within the intersection of these three groups, including the colourless glass and a white glass that does not exhibit the high calcium levels seen in

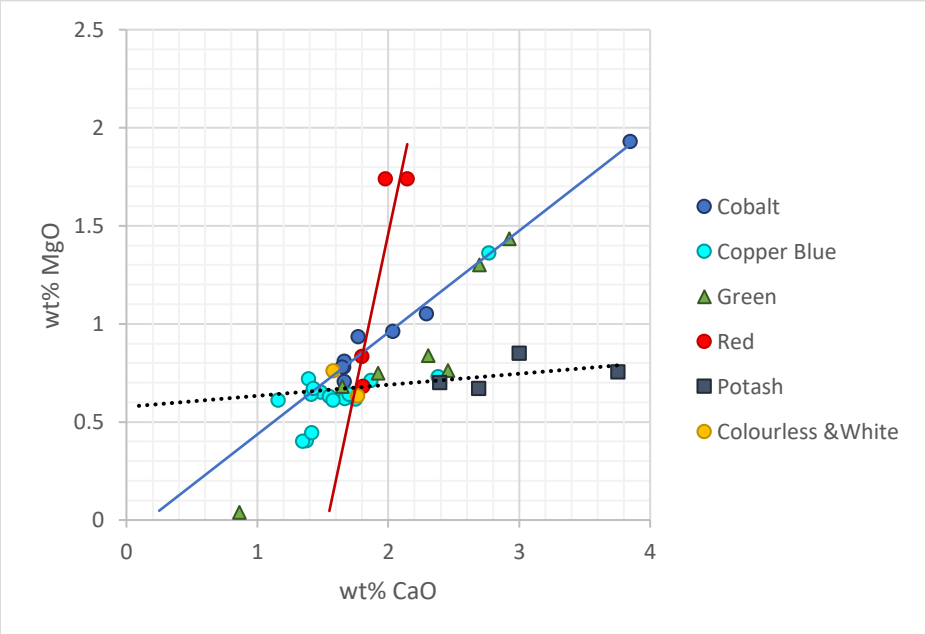


Figure 5.10: Magnesium against Calcium in glass from Frattesina, sorted according to colour.

FRAT 58b. Attention should be drawn to the potash trend. Several green glasses as well as turquoise fit along this trend, including two samples that have very similar levels of calcium and magnesium to one of the potash glasses. These are the mixed alkali Frat 9 (LMHK, green), Frat 51 (LMHK, turquoise) and Frat 20a (potash, turquoise). Despite this, the LMHK glasses do not exhibit elevated levels of potash, having respectively, 9.41 wt% and 7.7 wt% K_2O. One possible suggestion is that this is due to the addition of a relatively pure calcium. This matches with FRAT 58b having similar levels of magnesium to the glasses along this trend. While these glasses do not show elevated antimonate as would be expected for the addition of the opacifier calcium antimonate, antimony was not detected for FRAT 58b. Overall, it might be suggested that different calcium sources may have been considered more appropriate for colouring red or cobalt glasses, although not exclusively. This would then imply that the base composition of the glass is roughly between 1.4-1.8 wt% CaO and 0.6-0.8 wt% MgO.

5.1.2 Ca/Al:Na/Mg

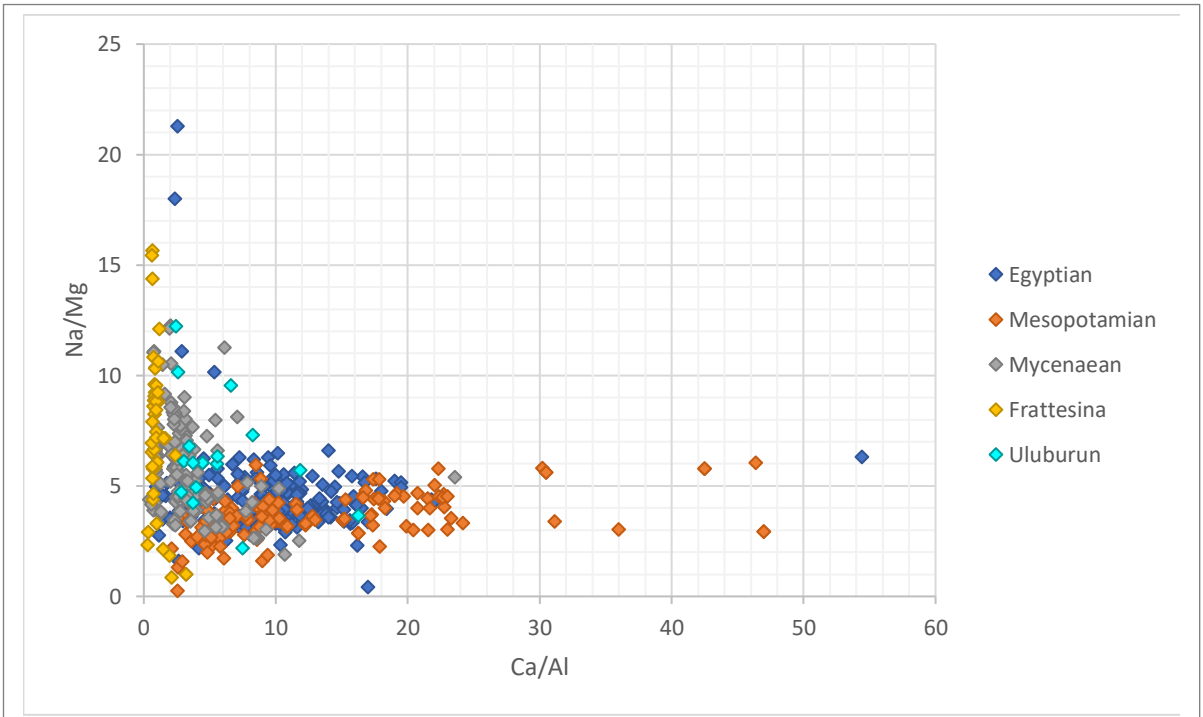


Figure 5.11: A biplot of the ratio of Sodium to Magnesium against the ratio of Calcium to Aluminium in Bronze Age Glasses

As well as considering the wt%, ratios of elements can be useful for understanding the composition of ancient glass. Figure 5.11 shows the ratio of Calcium to Aluminium plotted against the ratio of sodium to magnesium. Calcium and aluminium can both be derived from a relatively impure silica source or the soil conditions of the plant ash. Sodium and magnesium are both considered to be components included in the plant ash. However, sodium can come from natron and magnesium may also be included as an impurity in the silica or lime source. Egyptian and Mesopotamian glass show variation in the calcium to aluminium ratio. This may suggest that calcium and aluminium entered the glass batch through different ingredients or that the source of the ingredients was variable. Figure 5.12 looks at the composition based on different Mesopotamian glasses. It shows variation based on location, with some overlap between Nuzi and Nippur although ultimately Nuzi has on average a higher ratio of calcium to aluminium. Tell Brak shows more variation than either Nuzi or Nippur. Both the glasses from Nuzi and Tell Brak have been noted to contain low levels of lime and

alumina compared to the contemporary sites of Amarna and Malkata (Shortland & Eremin 2006, 48). The glass from Nippur was found in a later context, but based on inscriptions is believed to be from the 14-13th centuries B.C. (Walton et al. 2012, 836). Most of the non-blue Nuzi glass tends towards the lower ratios of calcium to magnesium. The majority of the Egyptian glass overlaps with that of Nippur while tailing off towards the Nuzi cluster. This may suggest that Nippur utilised similar resources as Egyptian glass compared to Nuzi and Tell Brak. However, it is likely that the low ratio of calcium to aluminium in the glass from Nippur is due to elevated alumina. Cobalt does not appear to be correlated with alumina for the Nippur glass, unlike that of Egypt (Walton et al. 2006, 488). This may suggest a less pure silica source, or a plant ash richer in alumina. Mycenaean and Egyptian glass exhibit lower ratios of alumina to calcium, although this is likely linked with the use of an alumina rich cobalt colourant. The influence of cobalt with the associated impurity aluminium can likely provide an explanation as to the lower ratio seen in Mycenaean glass. This is because Mycenaean glass is predominantly coloured with cobalt or copper cobalt (59.3% of the Mycenaean glass used in this meta-analysis). This does not hold for the glass from Frattesina, which does not exhibit higher alumina in its cobalt blue glass. Instead, the low ratio is likely indicative of its lower calcium content.

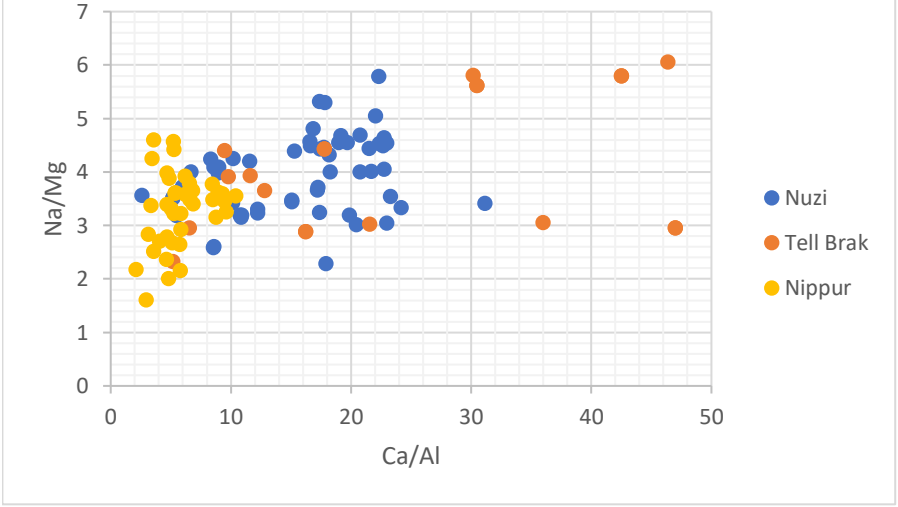


Figure 5.12: Mesopotamian glass, sorted by location

In contrast to the trends seen in Egyptian and Mesopotamian glass, the glass from both Mycenaean Greece and Frattesina have little variation in their ratio between calcium and magnesium. Conversely, they exhibit a greater range of ratios for sodium against magnesium. While

the ratios between sodium and magnesium are similar, this does not suggest that a similar plant ash is being used. The potash glass can be seen at the lower end, having a ratio between 0.85 and 2.15 sodium to magnesium. As the potash glass has similar levels of magnesia to the mixed alkali glass and the low ratio is due to the soda wt%. Due to the similar magnesia wt%, it is likely that either the potash source contained magnesia or it entered with another component. The variability across the mixed alkali glass may suggest that the magnesia came in a different component, causing greater variation in relation to soda.

Four Egyptian glasses also have higher ratios of sodium against magnesium and these are two BM5s (a copper cobalt and white sample), UP 38 (Cobalt) and COP 6 (white). A significant proportion of the glass from the Uluburun also exhibits higher sodium to magnesium ratios. This is of interest as trace element analysis on three of these glasses show that they correlate well with glass from Egypt (Jackson & Nicholson 2010, 299). This gives firm indication that the trend in Mycenaean glass is not linked with local production or acquiring the glass from locations other than Egypt. However, this does not explain why Egyptian glass rarely exhibits similar ratios between sodium and magnesium.

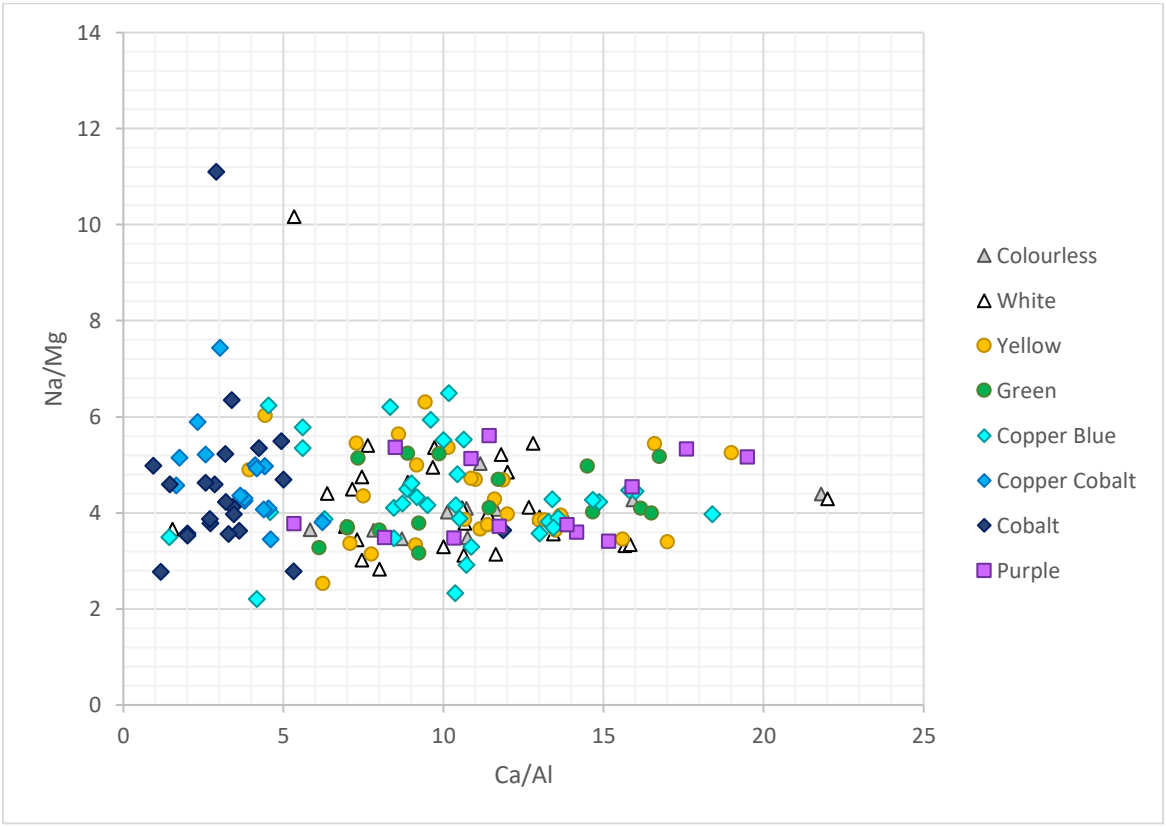


Figure 5.13.1: Egyptian glass, sorted by colour

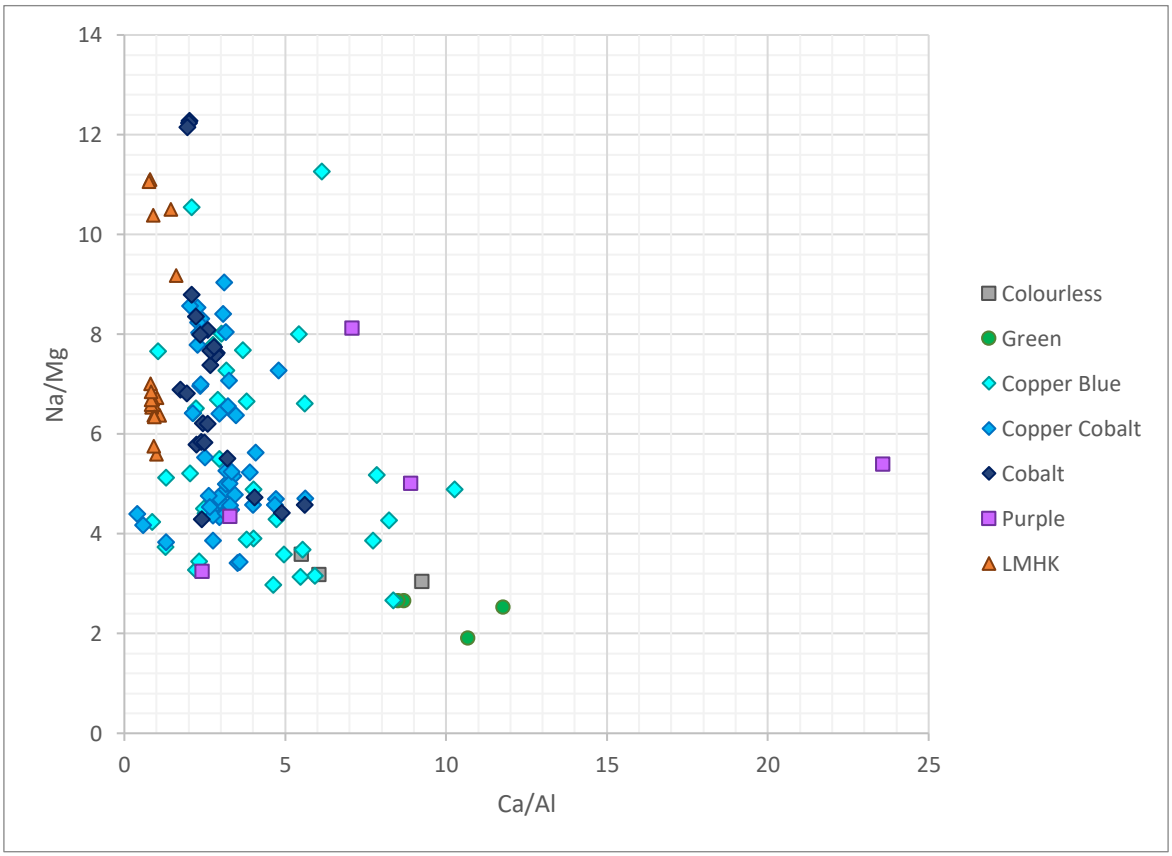


Figure 5.13.2: Mycenaean Glass, sorted by Colour

Figures 5.13.1 and 5.13.2 look at how different coloured glasses from Egypt and Mycenaean Greece sort depending on their ratios of Ca/Al and Na/Mg. Figure 5.13.1 has been set to have the same axis values as that of Figure 5.13.2 for ease of comparison. This loses a yellow sample with a high ratio of Calcium to aluminium (54:1), and a copper cobalt and white glass with a ratio of Sodium to Magnesium of over 15:1. It can be seen that cobalt blue glasses predominantly have a ratio of under 5:1 calcium to aluminium with the majority of other colours having higher ratios. These lower ratios are likely caused by the elevated aluminium associated with the cobalt source (Walton et al. 2006, 481). Some copper glasses have these low calcium to aluminium ratios, which is seen predominantly in glass from Mycenaean Greece compared to Egypt. Egypt does have some yellow and white glasses that fall into this category, although these are more the exception than the norm. In terms of sodium to magnesium, Mycenaean glass overlaps with Egyptian, but the Egyptian glass rarely has a ratio greater than 6:1. The higher ratios in Mycenaean glass can be associated with lower magnesia wt%. The average percentage MgO for Egypt is 4.16 wt% while for Mycenaean glass, it is 3.25 wt%. This shows that while the high alumina content does appear to be associated with cobalt glass, the variable magnesia is not.

Table 5.2 investigates how different blues fall within the ratios of Ca:Al and Na/Mg. A table with the raw data can be found in the Appendix (Table B).

		Egyptian	Mesopotamian	Mycenaean	Uluburun
Overall Percentage Blue Glasses	Copper	18.1%	51.1%	30.9%	37.5%
	Copper Cobalt	8.8%	32.1%	39.0%	12.5%
	Cobalt	11.4%	0.0%	20.3%	43.8%
	Blue Total	38.3%	83.2%	90.2%	93.8%
Ca:Al < 5:1	All Colours	24.4%	13.9%	80.5%	62.5%
	Blue Total	20.7%	12.4%	78.9%	62.5%
	Copper	2.1%	0.7%	21.1%	12.5%

	Copper Cobalt	8.3%	11.7%	38.2%	12.5%
	Cobalt	10.4%		19.5%	37.5%
Na:Mg > 6:1	All Colours	6.2%	0.7%	37.4%	62.5%
	Blue Total	3.6%	0.7%	36.6%	62.5%
	Copper	1.6%	0.7%	10.6%	12.5%
	Copper Cobalt	1.0%		13.0%	12.5%
	Cobalt	1.0%		13.0%	37.5%
Ca:Al < 5:1 & Na:Mg > 6:1	All Colours	3.6%		34.1%	37.5%
	Blue Total	2.6%		34.1%	37.5%
	Copper	0.5%		8.1%	
	Copper Cobalt	1.0%		13.0%	12.5%
	Cobalt	1.0%		13.0%	25.0%

Table 5.2: Percentage of different glasses having ratios under 5:1 for Ca:Al and over 6:1 for Na:Mg in Bronze Age HMG blue glass.

This table shows the heavy use of the colour blue, especially in Mycenaean glass. The majority of the glass that fall into the ratios of either under 5:1 for calcium to aluminium or over 6:1 for sodium to magnesium are cobalt and copper cobalt blue glass. Mycenaean copper blue glass also fits within these categories. The table highlights that glass with these ratios are predominantly from Mycenaean Greece and the Uluburun. This is curious as trace element and isotope analysis has shown that both these glasses come from Egypt (Henderson et al. 2006, 7; Jackson & Nicholson 2010, 299). For the most part, the percentage of glass from the Uluburun falling within a certain ratio matches closely with those from Mycenaean Greece. In both cases, they have a greater percentage within a category than those from Egypt or Mesopotamia. Based on the cargo, the Uluburun is believed to be contemporary to Amarna, which along with Malkata, make the bulk of the glass from Egypt used in this study (Bachhuber 2006, 347). This makes the different ratio of

sodium to magnesium seen on the Uluburun of interest, especially as it pairs with the ratios seen in Mycenaean glass.

5.1.3 Principal Components Analysis

Principal Components Analysis reduces the dimensionality of large data sets which increases interpretability but also minimises data loss (Cadima & Jolliffe 2013). PCA was carried out on the data using MATLAB. Four categories were used: Egyptian, Mesopotamian, Mycenaean Greece and LMHK. This was done to increase understanding of the relationship between the variables as well as to identify subgroups. The proximity of the variables (different elements) to each other and the three components (1, 2 and 3) show correlation. The use of three dimensions helps to identify the relationship between the variables, as two dimensions may obscure a third component. While the graphs can be engaged with three dimensionally using MATLAB, they must be viewed into two dimensions for this study. Efforts were taken to ensure maximum visibility of the relationship between the different variables, although this is not always clear.

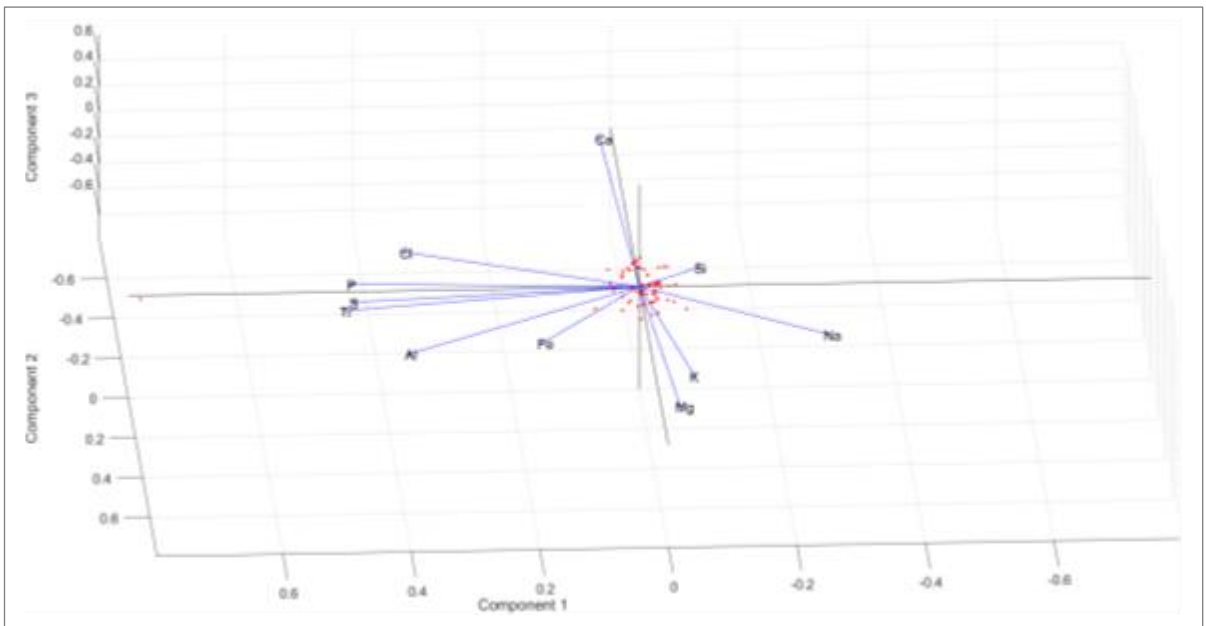


Figure 5.14: PCA of Mesopotamian glass. P, S and Ti are closely associated with Component 1. Al and Fe and, Cl are also associated but less so. Mg and K are closely associated with Component 2. Ca, Na and Si are not closely associated with other elements

The number of Mesopotamian samples included is lower than the total used in this meta-analysis. This is due to some studies not reporting the content of minor elements such as phosphorus, sulphur and chlorine or reporting minor elements with ppm. As can be expected for a plant ash glass, magnesium and potassium plot closely together. While sodium does not appear closely correlated with these elements, it does not plot far off. Impurities associated with silica (Al, Fe and Ti) cluster together along with phosphorus and chlorine. There are no clear groups and the points plot predominantly along the Component 2 axis. This is the axis that Mg and K closely associate with, potentially suggesting that the majority of the variation in Mesopotamian glass is associated with plant ash.

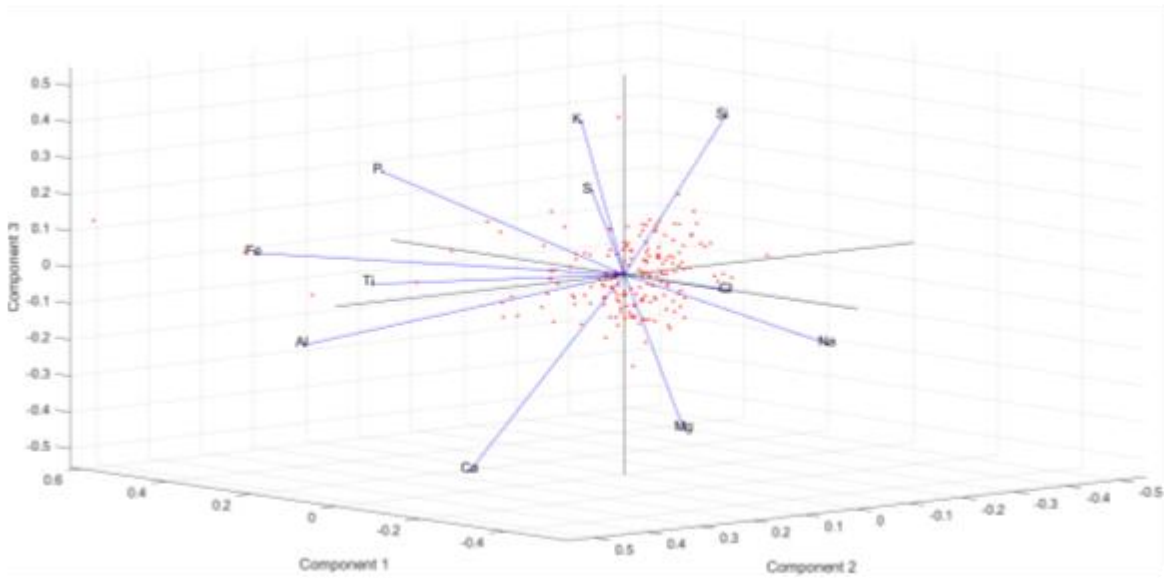


Figure 5.15: PCA of Egyptian glass. Al, Fe, Ti (impurities of Silica) are associated. These elements, with silica have a positive value for component 1.Other elements have a negative value. K, P and S are loosely associated. Na and Ca are also loosely associated. Na, Cl, Mg, Ca and Ti have negative values for Component 3.

The Egyptian glass shows less clear correlation between the different variables. Like Mesopotamia, no clear groupings can be identified for the samples. Potassium seems to be associated loosely with both phosphorus and sulphur. This suggests that these elements

	Non-cobalt glass	Cobalt glass	Non-Cobalt: Cobalt
Si	63.16	62.86	1.00
Al	0.80	2.47	3.07
Ca	7.52	7.46	0.99
Mg	4.17	4.12	0.99
Na	17.45	18.45	1.06
K	2.17	1.05	0.48
Fe	0.46	0.54	1.19
Ti	0.08	0.09	1.12
Co	0.02	0.14	6.53
Cu	0.58	0.18	0.32
Mn	0.17	0.19	1.14
Ni	0.01	0.07	5.45
Zn	0.08	0.14	1.82
As	0.03	0.03	0.77
Sn	0.07	0.02	0.22
Sb	0.83	0.35	0.42
Ba	0.03	0.03	1.00
Pb	1.03	0.13	0.13
Cr	0.01	0.01	1.00
P	0.18	0.13	0.76
S	0.31	0.31	0.99
Cl	1.01	1.02	1.00

Table 5.3: The overall compositional difference between cobalt and on-cobalt Egyptian glass.

are potentially associated with the plant ash. Sodium and magnesium are not correlated well with each other or potash. However, variables associated with silica (Al, Fe, Ti, Si) have positive values for Component 1 while impurities associated with plant ash have negative values. The plant ash variables can be divided in a similar way with Component 3. Na, Cl, Mg and Ca all have negative values while K, P and S have positive. This may suggest that in the plant ash, these elements are associated. Table 5.3 shows the ratio between the elements in cobalt and non-cobalt blue glass. Si, Ca, Mg Na, Ba, Cr, S and Cl remain very similar between the two groups, likely suggesting the same source for these two groups. It is curious that despite sulphur's correlation with potassium using PCA, there is little difference between the groups. Phosphorus is lower in cobalt glass, like potassium. Other elements that are lower in cobalt blue glass are Cu, As, Sn, Sb and Pb. These are more likely to be associated with colourants and are likely lower due to this. This may suggest that phosphorus and potassium are associated in both glasses but experience a decrease in cobalt blue glass.

As Mycenaean glass is believed to have come from both Egypt and Mesopotamia, this is likely to impact PCA as Egypt and Mesopotamia have different principal components. As the glass is predominantly cobalt blue, it might be expected to align closer to Egyptian glass. Like Mesopotamia, the Mycenaean glass has potassium and magnesium closely associated. Iron and aluminium show

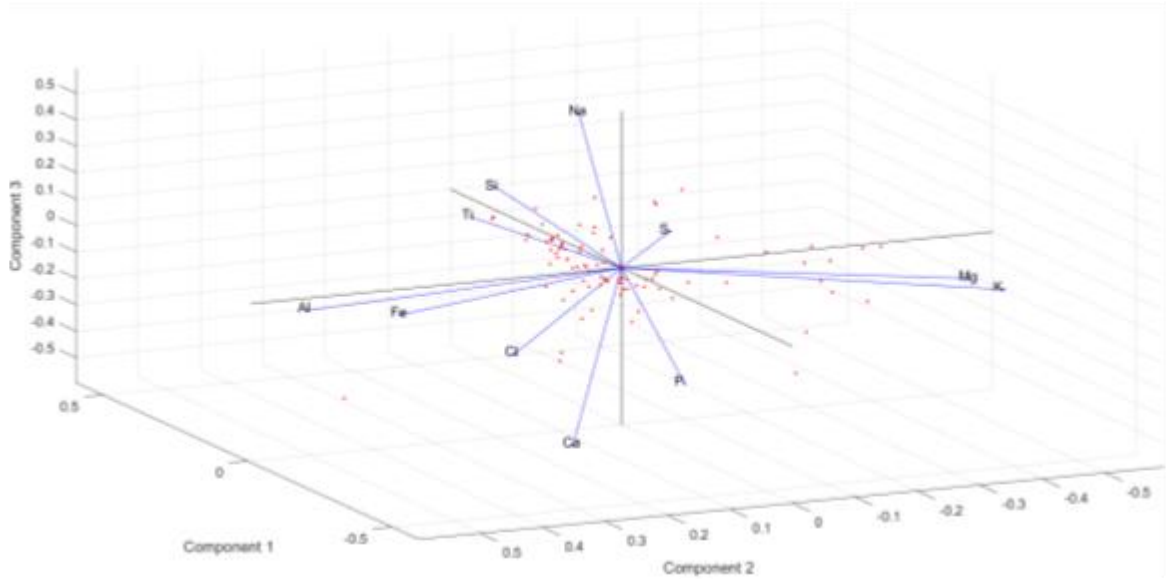


Figure 5.16: PCA of Mycenaean glass. Magnesium and potassium show a strong correlation midway between components 1 and 2. Al and Fe show potential correlation and a less clear correlation may be seen between calcium and phosphorus.

potential correlation although this is not too closely associated. The lack of strong relationship in silica associated impurities in Egyptian and Mycenaean glass could be linked with the elevation of aluminium in cobalt glass. This may obscure association when using PCA. Like other HMGs, there are no clear groupings in the Mycenaean glass. Calcium may show a loose relationship with phosphorus, although phosphorus is equally close potassium.

As a whole, PCA does not appear to be of much use in HMGs. It may provide some evidence of relationship between variables but it is hard to tell if this holds. It may prove to be advantageous to perform PCA alongside bi-plot graphs to identify where elements show reasonable correlation. This may help to identify plant ash use and potentially help to identify further methods to discriminate between Egyptian and Mesopotamian glasses. Egyptian and Mycenaean glasses are complicated by the presence of glasses with different compositions. This is namely the low potash cobalt glass in Egypt and a mixture of Mesopotamian, Egyptian and low potash cobalt glass in Mycenaean Greece. In theory, different groups may become identifiable through the use of PCA, but this is not the case for these glasses. However, the mixed alkali presents a different story. The mixed

alkali is composed of glass from Elateia and Frattesina. With the mixed alkali glass, three distinctive groups can be identified on a two-dimension PCA biplot looking solely at Si, Na, K, Ca, Mg and Al, as seen in Figure 5.17.

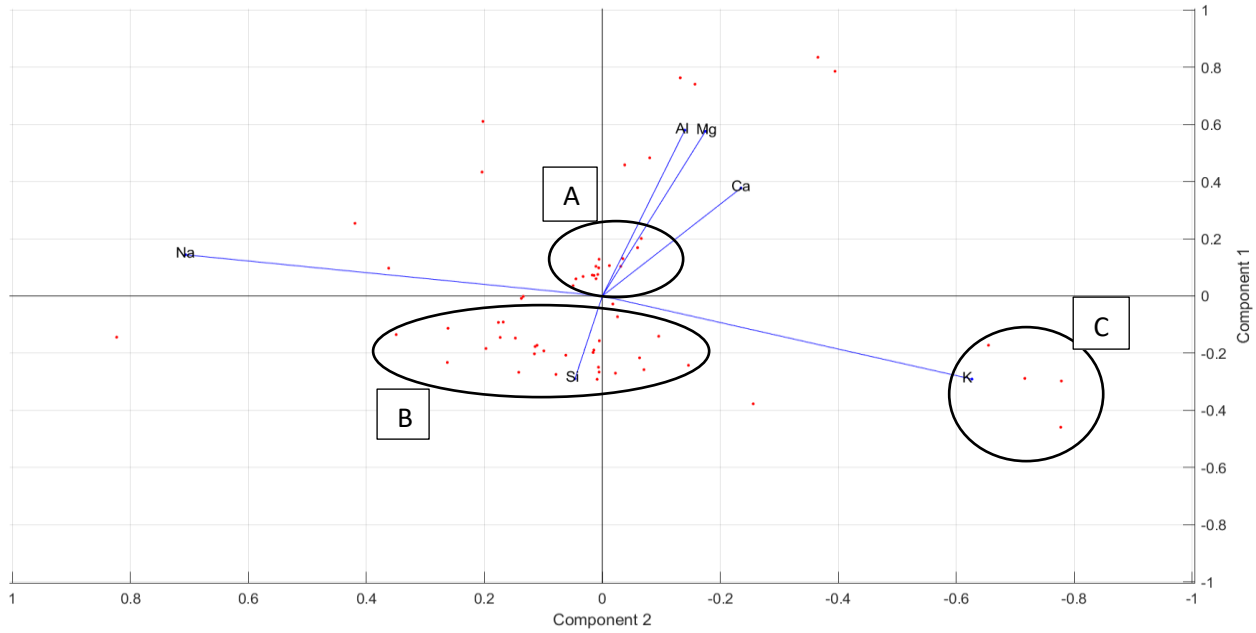


Figure 5.17: Two Dimensional PCA analysis of mixed alkali glass from Elateia and Frattesina, showing three different groups

Group A sits with the calcium, aluminium and magnesium variables and is predominantly glass from Elateia (11) with two green and two copper cobalt samples from Frattesina. This group tends to have higher lime, magnesia and alumina than Group B. While Group B sorts near the silica variable, it does not have higher silica than Group A or C. This group has 6 of the Elateia glasses and 21 from Frattesina. The final group is Group C, which is the potash glass from Frattesina. This group is clearly distinguished from

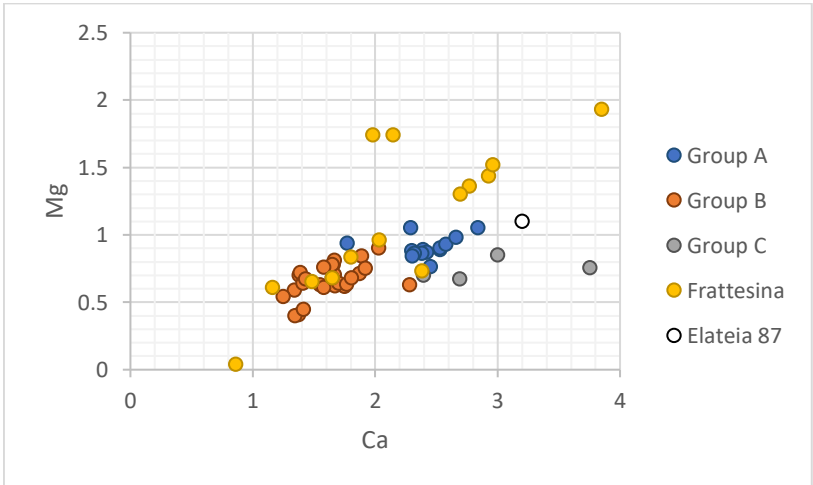


Figure 5.18: Magnesium and Calcium in LMHK glass, sorted by groups identified via PCA.

the other glasses in standard biplots due to the high potassium levels. 14 glasses from Frattesina do not fit into either of these categories, which includes a mid of colours as well as the majority of the red glass. Only one of the Elateia glasses does not fit into either group and this is Elateia 87, a white glass that functions as decoration. While overall a strong correlation is seen between calcium and magnesium in the LMHK glass, this is not seen as clearly within the groups with their respective R^2 values being considerably lower. This is because the end points of the trend line do not fit into either group, instead belonging to the remainder of the glass from Frattesina – See Figure 5.18. Group A and C both have a higher calcium to magnesium ratio than Group B or the remainder of the glass from Frattesina. This potentially suggests a different calcium source for these groups.

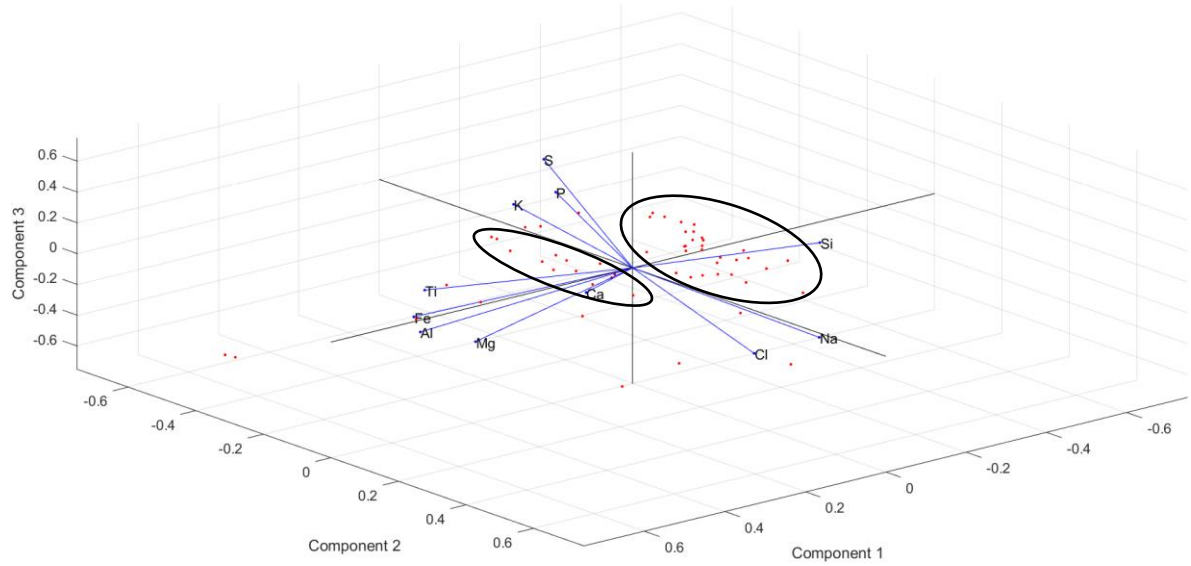


Figure 5.19: Three dimensional PCA of Mixed Alkali glass. Groups A and B can be identified, although less clearly. The potash glass group cannot be clearly seen from this angle.

A further PCA was carried out on the LMHK, using the same variables as the HMGs and in three dimensions. This can be seen in Figure 5.19. Titanium, aluminium and iron all cluster together and also show a decent relationship with magnesium. Calcium appears to be loosely correlated with magnesium and phosphorus and sulphur. Chlorine is correlated closest with sodium. Silica, titanium aluminium, iron, magnesium and calcium all plot along component 1 while sodium, potassium and chlorine are more associated with component 2. Sulphur and phosphorus are closer to component 3

and least associated with component 2. Group A has greater association with silica impurities than Group B. They both have greater variation along Component 2, which is associated with the alkali. This suggests two silica sources with Group B having a purer source. It also suggests that magnesium is associated with the silica source, which contrasts with HMGs where the magnesium appeared to be a component of the plant ash. This would also potentially support the alkali source being relatively pure. Furthermore, while phosphorus offers a reasonable correlation with potash in HMGs (specifically cobalt), it provides a much stronger correlation with calcium in LMHK glass, as seen in Figure 5.20. A correlation between calcium and phosphorus can be interpreted as the use of bone ash, however the low levels of both these elements (and the high ratio of calcium to phosphorus) may suggest otherwise (Towle 2001, 53). It is interesting to note that in Group A, the higher phosphorus glass is all from Elateia, while the lower phosphorus glass is the four samples from Frattesina. The source of the alkali in LMHK glass has been of debate. Potentially a leeched wood ash, natron contaminated with potassium salts or manurial soil/latrines (providing saltpetre and sodium nitrate) may have been used (Henderson et al. 2015, 2). With Figure 5.19 showing both Na and K with low or no association with other elements and both plotting close to Component 2, it seems that this may support the use of a more chemical source (i.e. potassium contaminated natron or manurial soil).

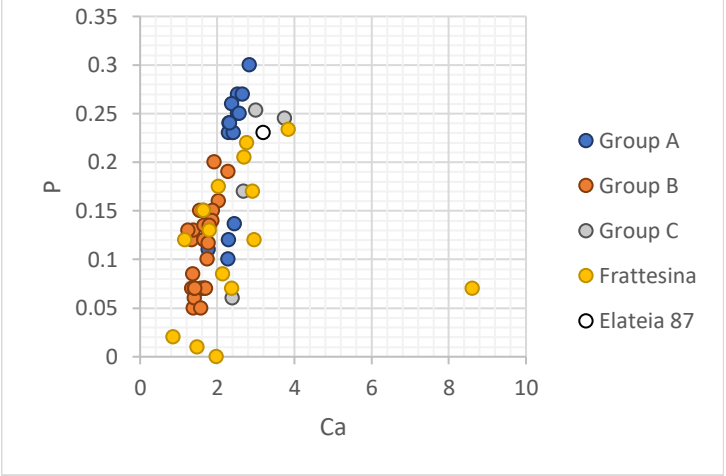


Figure 5.20: Phosphorus against calcium in LMHK glass, sorted by groups identified using PCA.

The three groups tend to correlate together in trend lines for graphs of aluminium, iron, titanium and magnesium. However, when these elements are plotted against calcium, there is some variation. Group A and B predominantly plot along a similar trend with group A having a lower wt %

of calcium. However Group C has elevated calcium levels relative to group B. As Group C plots along the trend line for the other elements, this suggests that calcium is potentially added to this glass. As the glass also has higher potash, it might be suggested that the excess calcium entered with the potassium. However, calcium does not correlate well with potassium (a R^2 value of 0.18). With only four samples, this is not overly surprising. Further identification of LBA potash glass and analysis would be of use in understanding the calcium component. Furthermore, while it may be tempting to suggest that the presence of potash glass may suggest mixing between a soda rich and potash rich source, the difference in calcium appears to suggest that the potash glass is not behind the mixed alkali composition. This is despite evidence on Frattesina 20 for the mixing between a high copper potash glass and a mixed alkali copper glass (see Appendix, FRAT 20a and FRAT 20b). With three potential groups and evidence for mixing between two of them, this shows the complication of ancient glass analysis.

Considering the alkali, a trend is seen from Group C with high potash to the higher soda glasses, as seen in Figure 5.21, although as mentioned it does not necessarily appear that mixing with the potash glass is the cause of the mixed alkali composition. Group A forms a strong cluster compared to the other groups. This may suggest that it is a single batch. The majority of the glass in Group A is copper cobalt (there are only two exceptions from Frattesina) which may support this. It may also suggest a specialisation in copper cobalt glass. The two glasses that are not copper cobalt are apple green and potentially coloured through iron. These glasses do not show elevation in

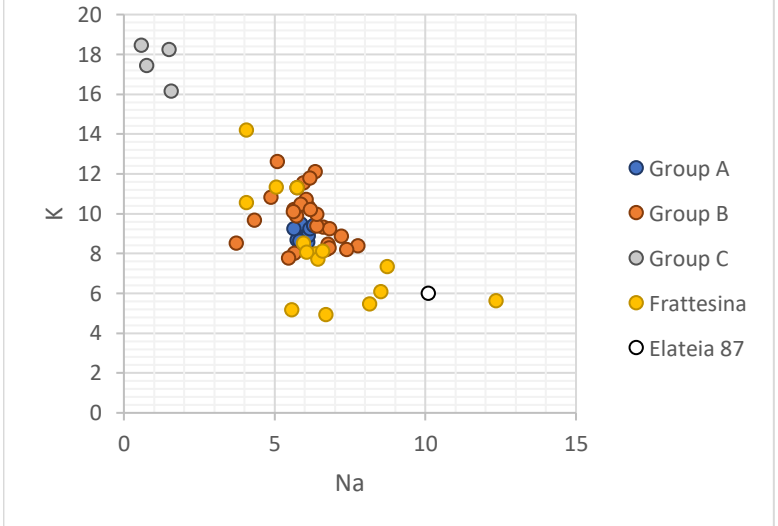


Figure 5.21: Potassium against sodium in LMHK glass, sorted by groups identified using PCA

colourants, which would mean the only purposefully added colourant in this group is the copper-cobalt, whether as two seperate colourants or in a copper rich cobalt source, as suggested by Smirniou and Rehren (Smirniou & Rehren 2013, 4739). Group B is predominantly copper blue (14 out of a total 27), although there are 7 copper cobalt glasses. These copper cobalt glasses from Group B have lower copper (on average (0.6 ± 0.29 wt%)) compared to that of Group A (1.41 ± 0.58 wt%). It is unclear whether this is due to Group A being single batch or produced at a different site. If Group A is a batch, the difference in copper content may support independent copper and cobalt colourants. Like Group A, Group B has pale green glass samples. It also has a colourless sample. None of these glasses appear to have added colourant. One red sample is also in Group B, which may be fitting with copper being the predominant colourant used in this group. Four of the glasses have a copper to tin ratio between 9-12.5:1 which strongly suggests the use of bronze for these glasses. Only in two samples, was tin not detected. Five of the remaining copper glasses have a ratio under 25:1 for copper to tin, which may potentially suggest bronze or a mixing between copper and bronze coloured glasses. The last two copper blue glasses have a much higher ratio, suggesting a pure use of copper. This potentially indicates the mixed use of copper and bronze in colouring glass within one production site (if the groupings identified using PCA represent different production).

PCA has proved to be a useful tool for investigating mixed alkali glass. It has identified two potential groups which can be further investigated using biplots. The variable components plotted on PCA graphs, along with biplots may be able to provide further understanding on the relationship between the various components of glass. The use of large data sets allows for a general overview of the general composition, which may help to further understanding of glass production. While PCA did not show groupings for HMGs, three groups can be seen for LMHK glass. This may be due to the smaller data set, reducing the amount of overlap between groups. Further research is needed to investigate how PCA may help to further understanding of Bronze Age glass.

5.2 Discussion

Considering the meta-analysis, two key points to discuss are:

- Cobalt in Egyptian and Mycenaean glass – namely the low potash in both and the lower magnesia in the Mycenaean
- The use of colour in understanding the production of glass and its wider impact

5.2.1 Blue in Egyptian and Mycenaean Glass

Egyptian and Mycenaean cobalt blue glass shows a slight variation in composition compared to other coloured glass. It is furthered by an additional variation in Mycenaean (and the Uluburun) glass, despite trace element and isotopic analysis supporting an Egyptian origin for these glasses. The lower potash seen in cobalt blue applies to both Mycenaean and Egyptian glass, while magnesia is in relation to Mycenaean glass (and the Uluburun – whose destination is believed to be Mycenaean Greece) (Bachhuber 2006, 347). Any explanation seeking to explain either of these points should not counteract the other. For instance, if a plant ash glass is mixed with natron (to achieve the lower potash and magnesia), then an explanation should be able to qualify why Egyptian glass has higher magnesia. With natron contributing around 1 wt% oxide for both potassium and magnesium, this would suggest a plant ash with very low potash (potentially contributing as low as 0 wt%), and magnesia of at least c. 0.5 wt% for Mycenaean and closer to 2+ wt% or greater magnesia for Egyptian glass. Wood and Hsu offer the suggestion that a natron (or other soda mineral) based cobalt rich frit was used as a colourant, with subsequent recycling of glass reducing the cobalt levels and increasing other elements such as calcium,

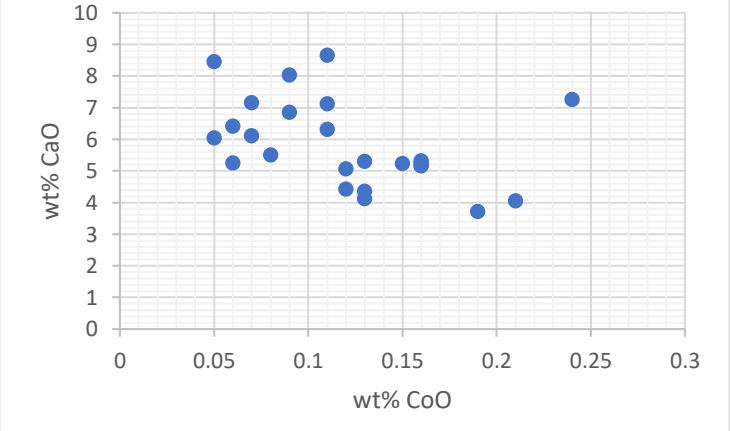


Figure 5.22: Calcium against cobalt in Mycenaean cobalt blue glass

sodium and potassium (Wood & Hsu 2019). While it might not be expected to see variation over time at Amarna and Malkata as they are 14th century sites, the Mycenaean glass spans a greater range of time, so might be expected to reflect this trend. However, while the trends are negative, there is low correlation (calcium has the highest R^2 value at 0.39, potassium is 0.02 and sodium is 0.01)[1]. The Mycenaean cobalt glass with the lowest potash and magnesium wt % oxides are dated to LH IIIB-C while the glass discussed by Wood and Hsu corresponds with LH IIIA1-A2 (Wood & Hsu 2018). This could be explained by the glass being deposited at a later date. It is worth noting that this does not explain the overall lower magnesia in Mycenaean cobalt blue glass compared to Egyptian. If a plant ash was the source of the alkali, it would have to be soda rich, potentially grown near the soda rich Wadi Natrun (Rehren 2001, 486). Analysis of plant ash glass has shown that potassium is generally higher than that found in glass, although not all of this would have reacted with the silica, as chlorides and sulphates are fairly unreactive and form a scum (Barkoudah & Henderson 2006, 311). Hence, if a plant ash was used, the low potash might be explained by the potassium in the plant ash being unreactive in the plant ash used in cobalt blue glass production. Further, the correlation between phosphorus and potassium in cobalt blue glass supports the use of plant ash.

While this gives support to the use of plant ash, it does not explain the lower magnesia in Mycenaean glass, especially as in other aspects, the cobalt blue glass correlates with the Egyptian cobalt blue glass. With the Uluburun exhibiting similar patterns and also being contemporary of Amarna (based on cargo; Bachhuber 2006, 347), this may imply that the glass found in Mycenaean Greece was made for export. It is uncertain whether this would have been a conscious decision to use a glass with a different plant ash. Potentially, a separate production site may be involved more heavily with exporting material and use the same plant used for domestic cobalt but grown on a different geological bed. This could have resulted in a glass with a higher soda to magnesia ratio. If a site was more involved with producing glass for export, it may have been advantageous to be closer

[1] KN-P-134 (from Henderson et al. (2009)) is not included as it does not correspond to the bulk of the data for cobalt blue glass.

to the maritime network for ease of transport. Glass produced primarily for domestic consumption could have other factors influencing location such as proximity to secondary working sites, royal residencies, or internal transport networks. Another potential suggestion is that the plants used in glass production were harvested during a different season. It has been suggested by Barkoudah and Henderson that the plants were harvested at the end of summer and that glass was principally produced during the late summer to early autumn during the Bronze Age (Barkoudah & Henderson 2006, 301). The winter months have generally been considered riskier for sailing (the 'bad season') due to chaotic weather and which may have made coastal sailing extremely treacherous, if not impossible (Tammuz 2005, 145 & 156). It might be suggested that glass made for export was produced on a smaller scale to coincide with favourable weather. Some have suggested that the two Mycenaeans onboard the Uluburun may have been overseeing the transport of a reciprocity gift (Bachuber 2006, 353). This may support a specific request of glass and hence a different production season. The drawback to this suggestion is that glass is a non-perishable material. There is no reason why glass ingots could not have been kept for later shipping when the weather would have been more favourable. Potentially, the majority of the main production of glass may be used domestically necessitating a smaller, secondary production for export. An exploration into the seasonal and regional variation of plant ash may help to understand the compositions seen in Mycenaean and Egyptian glass.

5.2.2 Colour in Bronze Age Glass

Colour is thought to have played a significant role in early glass with current thought being that glass was an imitation of semi-precious stones (Brøns 2019, 322). One of the key stones of note is lapis lazuli, which dark blue glass is believed to imitate. The price of lapis lazuli is believed to have remained close to that of silver, with some level of fluctuation (Warbuton 2019, 18). Both cobalt and copper could be used to achieve a dark blue glass, with copper being the colour predominantly used in Mesopotamia. This means that both copper and cobalt can be used as an imitation of lapis lazuli.

Similar to this, glass coloured by both copper and cobalt could produce lighter shades of blue, occasionally turquoise in shade. This is however, much less frequent and most of turquoise blue glasses are coloured using copper. The majority of the glass is blue. Even in Egypt, which is noted for having a more diverse colour range, blue is the predominant colour (38.7% of the Egyptian glass in this meta-analysis are a shade of blue) (Shortland et al. 2018, 775). For both Mesopotamia and Mycenaean Greece, around 90% of the glasses are blue as compared to 60.5% of the samples from Frattesina. This seems to suggest a strong preference for the colour blue, which may be linked with its imitation of semi-precious stones, such as lapis lazuli. The colours of blue glass are often divided into turquoise, light blue, blue and dark blue, which can help identify whether the glass is imitating lapis lazuli or turquoise. While the far ends of the spectrum (turquoise and dark blue) are more readily recognisable, light blue and blue can be less clearly defined. Mycenaean glass shows a strong preference for dark blue, while Egypt and Mesopotamia have a greater percentage of blue glass classed as 'blue', with Egypt leaning towards dark and Mesopotamia towards turquoise. Frattesina, likewise, has more turquoise glasses. The strength of the colour will be impacted by various factors such as the level of colourants, the thickness of the glass and weathering, among other factors. This makes it difficult to identify whether or not this represents a preference for lapis lazuli or turquoise is difficult to identify. Warburton suggests that the absence of lapis lazuli and the abundance of dark blue glass in Mycenaean glass could potentially be linked with the high cost of lapis lazuli (Warburton 2019, 19). In this way, the predominance of colour may be linked with a lack of access to material or some other purposeful choice to use the imitation over the original. Furthermore, the preference for blue may be linked with a colour preference, rather than a material one. That blue is the predominant colour across these four groups is curious, potentially suggesting either a cross cultural influence or a more innate attraction to blue, whether due to environmental or biological influence.

Caution must be taken to avoid concluding that blue was universally popular. Just as we can divide blue by colour, other cultures can have distinct words for the two shades, such as in Russian

(Winawer et al. 2007, 7780). Potentially there may have been such distinctions in these four groups. The general shift in the shade classification from turquoise to dark blue may suggest that the distinction was no more than shade. This is especially true for the HMGs. This is not so much the case for Frattesina with only two glasses not sorting into the categories of dark blue or turquoise. These glasses are identified as blue, which can be considered somewhat different from turquoise as turquoise has more green tones. This makes it especially interesting that turquoise is the predominant colour, followed by green and then blue. This may suggest that the blue-green colour of turquoise was more important in Frattesina or potentially turquoise and blue were viewed as separate colour groups. The significance of green is hard to identify. Half of the green glasses have above 0.1 wt% CuO, lower than 0.1 wt% copper suggests the content comes from contamination with a copper or bronze smelting vessel (Duckworth 2011, 54). The rest are likely coloured by the iron content, although the copper and iron levels of these green glasses are not higher than in the white and colourless glasses. Most of the green glass analysed are ingots while the white glass is as decoration or a bead and the colourless glass is a strip. This may mean that the green glass was originally intended to be colourless. The dark blue glass is also predominantly raw glass, although there is one sample which is a bead (FRAT 47). As such, it is not clear whether this gives a turquoise with a leaning to green or blue as a preference.

There is a strong preference for dark blue in Mycenaean glass. This is in contrast to Mesopotamia and Egypt, where blue (as opposed to dark blue) is preferred. This is potentially down to visual classification. A bead classified as blue may be seen as dark blue or vice versa. It is thus difficult to identify whether this represents a preference for dark blue or just blue. It seems possible that glass was made specifically for export to Mycenaean Greece, which would support a Mycenaean preference for dark blue over what was to available. Unlike Mesopotamia and Egypt, which made use of lapis lazuli and turquoise, these stones are rarely found in Mycenaean Greece (fewer than 40 lapis lazuli compared to c. 1650 amethyst beads) (Warburton 2019, 20). This might therefore suggest that while blue may be favoured elsewhere due to its connection to semi-precious stones, at most it

would be an indirect connection in Mycenaean Greece. As suggested by Warburton, this may have to do with the cost of lapis lazuli at the time (Warburton 2019, 18). It may be that lapis lazuli was used for other purposes. At Gla, lapis lazuli has been identified as a colourant in a fresco, which shows not only that the elites could afford lapis lazuli but also that artisans considered it suitable for use as a pigment (Brysbaert 2006, 261). In Egypt, glass vessels were decorated with yellow and white, believed to be a form of imitation of the mottling found in lapis lazuli (Duckworth 2011, 105). A similar effect is seen in the copper cobalt glass from Nippur, which shows the use of combeite to give this mottling effect (Walton et al. 2006, 481). On the other hand, Mycenaean glass does not tend to show this. Mycenaean glass is often in the form of relief beads, which have stylistically Aegean imagery. Relief beads are made from gold and glass (in some cases glass coated with gold) (Jackson & Wager 2011, 118). It may be that blue (and gold) were more suited thematically to relief beads. If, as suggested by Nightingale, blue was associated with protection, this would give good reason for the choice of blue (Nightingale 2008, 211). Conversely, these materials are likely more suitable to use as relief beads as they can be created using moulds.

With the ratio of Na:Mg being greater in Mycenaean glass and the Uluburun, it does appear that this glass is made for transport, whether purposely or accidentally. If glass was made specifically for the Mycenaeans, this may imply a degree of control over what colours were received. This would give firmer evidence for the significance of blue for Mycenaeans. It is hard, however, to identify if this is due to a culturally specific significance to the colour blue. This is because blue is the predominant colour in the glass of contemporary cultures, which may have impacted choice and preference. Blue is held for its calming properties (which appears to be cross cultural) and if this can be identified as innate to humankind, this may help to explain its dominance (Sterman & Sterman 2012, 196). It is, however, difficult to identify if something is inherent to humankind, as people and culture do not exist in a vacuum. As colours such as green and blue begin to appear in art during the move to urbanisation, environmental constraints may have influenced colour choice (Warburton 2019, 13). As faience seems to be linguistically linked with the sky in ancient Egypt, this may support

the idea that 'natural' colours take on a greater significance during urbanisation (Nicholson 2012, 12). However, green does not share the same popularity as blue in glass. A lack of green may be because of its use in other materials, such as cloth which does not preserve as readily (Gillis 2015, 520). The use of green in outfits portrayed in frescoes is rare, although this may not be representative of everyday reality (Muskett 2007, 44). It does appear that blue had significance although whether this is caused by an innate, wider cultural interaction or a specific cultural interaction is outside the scope of this dissertation.

6 CONCLUSION

Glass is an important material in the Bronze Age landscape. Due to its complex nature, it can be difficult to provenance glass. Bi-plots have frequently been used for glass analysis and continue to be a useful tool. Potassium and magnesium are key elements in glass composition and are useful for separating between the main compositions of HMG, LMG and LMHK. While potassium and magnesium cannot be used to distinguish between different production zones in the Bronze Age East, general trends can be seen. Mesopotamian glass has higher potash and Mycenaean glass has lower magnesia and potash. There are overlaps between these groups making it impossible to distinguish based on these categories. Cobalt blue glass shows some interesting tendencies, with potential trend lines between potassium and phosphorus, and magnesium and calcium. It seems likely that plant ash was used for these glasses and that potentially the stronger correlation seen may be linked with limited production zones or the use of same plant ash.

Ratios may be able to help further understand glass production. While the ratio of Ca:Al does appear to be impacted by the aluminium included in the cobalt source, the ratio of Na:Mg in Mycenaean glass and glass from the Uluburun appears to distinguish it from other Bronze Age HMGs. This is despite convincing evidence that this glass originated from Egypt. This potentially suggests that Mycenaean glass was produced separately to the bulk of Egyptian glass. Further

research into the seasonal variation of plant ash (specifically halophytes) may help identify if this was influenced by favourable trading conditions. The ratio of Na:Mg cannot provide clear distinction between Egyptian and Mycenaean glass, but there is a decent probability that the glass is Mycenaean (or Mycenaean-destined) if the ratio is higher than 6:1.

The use of PCA may provide further evidence for correlation between elements, although this cannot always be certain. It may be useful when paired with bi-plots to examine the components of plant ash. It does appear that PCA may be able to distinguish between different production zones or batches, either between LMHK glass or smaller data-sets. It was able to identify the potash glass as well as two other potential groups. Group A of these groups appears to have higher levels of impurities associated with silica as well as a tight composition of sodium to potassium. The copper-cobalt glass in Group A and Group B differ, with Group A having a higher copper content. This further supports different production zones or batches.

Overall, meta-analysis of Bronze Age Glass can provide useful information. With the breakdown by colour, it allows for a clearer identification of trends that might not otherwise be recognized. Caution should be taken as groups should not become too small to offer meaningful interpretations, as this is counter to the benefits of a meta-analysis. This dissertation has focused predominantly on cobalt blue glass as this group is a decent size and deviations have been identified, such as the lower potash (Shortland & Tite 2000, 147). Meta-analysis and the break down based on colour may continue to prove useful as more glass samples are analysed and the results published. The use of a wider array of tools to examine the results may also prove to be of further use, especially combined with bi-plots.

7 APPENDIX

Glass from Frattesina, collected and sampled by Professor Julian Henderson, averages were taken from 2-3 analysis from samples.

TABLE A

	Si	Al	Ca	Mg	Na	K	Fe	Ti	Co	Cu	Mn
FRAT 1	75.77	2.18	2.04	0.96	8.54	6.08	1.04	0.07	0.17	0.51	0.02
FRAT 2a	77.34	2.24	1.66	0.78	6.73	8.20	0.77	0.07	0.12	0.15	0.02
FRAT 4	75.40	1.73	1.67	0.81	6.05	10.71	0.82	0.03	0.08	0.64	0.02
FRAT 6	71.54	3.94	3.85	1.93	6.37	7.98	1.71	0.13	0.06	0.97	0.11
FRAT 7	77.23	2.00	1.67	0.71	6.78	8.47	0.71	0.06	0.24	0.44	0.03
FRAT 47	74.78	2.51	2.29	1.05	6.18	9.25	1.13	0.07	0.20	1.45	0.04
Frat 3	75.61	2.76	1.77	0.94	6.13	8.91	1.26	0.09	0.09	0.14	0.03
FRAT 48	75.52	1.94	1.65	0.78	7.21	8.87	0.97	0.06	0.09	1.02	0.03
FRAT 10	70.33	3.86	2.77	1.36	5.96	8.52	1.43	0.13	0.03	5.25	0.04
FRAT 17	74.68	1.86	1.75	0.62	5.88	10.48	0.57	0.06	0.01	2.67	0.01
FRAT 18	73.60	2.14	1.38	0.41	6.35	12.10	0.47	0.05	0.01	2.45	0.01
FRAT 19	71.50	1.53	3.00	0.85	1.57	16.14	0.56	0.06	0.01	3.33	0.02
FRAT 20a	70.83	1.65	2.40	0.70	1.50	18.23	0.51	0.04	bdl	6.46	bdl
FRAT 20b	72.67	2.12	1.35	0.40	6.18	11.78	0.42	0.04	bdl	2.29	0.02
FRAT 21	77.44	1.74	1.49	0.65	6.71	4.92	0.55	0.05	bdl	3.36	0.03
FRAT 23	75.10	2.04	1.55	0.63	6.83	9.23	0.62	0.06	0.02	3.65	0.04
FRAT 26	72.94	1.15	1.87	0.71	5.09	12.61	0.43	0.02	bdl	3.85	0.01
FRAT 43	76.04	2.04	1.67	0.62	5.63	10.09	0.63	0.06	0.02	3.36	0.04
FRAT 46	74.55	1.47	1.16	0.61	4.07	14.19	0.44	0.04	bdl	4.86	0.01
FRAT 51	74.44	2.15	2.38	0.73	6.44	7.70	0.82	0.07	0.02	3.29	0.04
FRAT 52	76.87	1.31	1.58	0.61	7.40	8.19	0.49	0.04	bdl	2.51	0.03
FRAT 54	75.85	1.80	1.39	0.72	6.41	9.39	0.62	0.05	0.01	4.10	0.03
FRAT 56	72.99	2.13	1.42	0.45	6.41	9.95	0.47	0.03	0.01	4.91	0.04
FRAT 58a	75.94	1.52	1.70	0.64	6.81	8.27	0.60	0.06	0.02	3.97	0.04
FRAT 60	78.40	1.52	1.41	0.64	5.66	8.02	0.59	0.06	bdl	3.90	0.04
FRAT 79	76.69	1.36	1.43	0.67	6.20	10.20	0.52	0.04	0.02	2.79	0.01
FRAT 2b	62.53	0.54	0.86	0.04	12.35	5.62	0.30	0.02	0.03	1.69	0.01
FRAT 8	75.78	3.63	2.30	0.84	5.83	8.62	1.18	0.10	0.02	0.08	0.01
FRAT 9	74.20	3.03	2.45	0.76	6.31	9.41	1.05	0.08	0.02	0.13	0.02
FRAT 11	69.42	3.59	2.70	1.30	6.07	8.07	1.46	0.11	0.04	5.60	0.06
FRAT 12	77.73	1.71	1.65	0.68	5.75	11.31	0.61	0.06	0.03	0.01	0.03
FRAT 14	74.89	1.17	3.76	0.76	0.76	17.43	0.42	0.04	0.01	0.02	0.02
FRAT 15	73.11	2.90	2.93	1.44	8.74	7.33	1.06	0.10	0.02	0.84	0.02
FRAT 28	79.72	2.80	1.92	0.75	4.34	9.66	0.71	0.04	0.02	0.05	0.03
FRAT 16	76.91	1.26	2.69	0.67	0.58	18.45	0.40	0.04	0.02	0.01	0.01
FRAT 27	75.14	4.40	2.96	1.52	8.15	5.45	1.64	0.11	0.02	0.70	0.01
FRAT 58b	71.86	3.62	8.62	0.87	5.57	5.16	0.82	0.07	0.03	0.10	0.05
FRAT 61	78.89	1.69	1.58	0.76	5.46	7.76	0.61	0.04	bdl	0.14	0.01

FRAT 13	80.70	2.62	1.77	0.63	3.73	8.50	0.63	0.04	0.01	0.08	0.02
FRAT 5	76.98	2.69	1.80	0.83	6.59	8.10	0.83	0.07	0.03	0.14	0.02
FRAT 22	74.89	1.20	1.81	0.68	4.88	10.83	0.45	0.04	bdl	5.10	0.01
FRAT 55	70.15	6.71	1.98	1.74	4.06	10.56	2.81	0.20	bdl	2.35	0.07
FRAT 57	68.11	6.68	2.15	1.74	5.07	11.33	2.64	0.18	0.01	1.83	0.07

	Ni	**Zn**	**As**	**Sn**	**Sb**	**Ba**	**Pb**	**Cr**	**P**	**S**	**Cl**	**Total**	
FRAT 1	0.16	0.01	0.17	bdl	0.38	bdl	0.01	0.01	0.18	0.02	0.21	98.46	Dark Blue
FRAT 2a	0.16	0.02	0.06	bdl	0.02	bdl	0.02	0.01	0.14	0.02	0.09	98.57	Dark Blue
FRAT 4	0.09	0.04	0.06	bdl	0.59	bdl	0.01	0.01	0.12	0.03	0.05	98.915	Dark Blue
FRAT 6	0.15	bdl	0.08	bdl	0.04	bdl	bdl	0.01	0.23	0.03	0.01	99.14	Dark Blue
FRAT 7	0.42	bdl	0.28	bdl	0.04	bdl	0.01	bdl	0.12	bdl	0.14	99.305	Dark Blue
FRAT 47	0.31	bdl	0.19	bdl	0.08	bdl	0.04	bdl	0.10	bdl	0.07	99.74	Cobalt Blue
Frat 3	0.05	0.03	0.05	bdl	0.06	bdl	0.02	0.02	0.11	0.03	0.06	97.99	Blue
FRAT 48	0.08	bdl	0.04	bdl	bdl	bdl	0.01	bdl	0.07	0.03	0.06	98.43	Pale Blue
FRAT 10	0.02	bdl	0.06	0.10	0.09	bdl	0.01	bdl	0.22	0.06	0.09	100.33	Turquoise
FRAT 17	0.01	bdl	bdl	bdl	0.01	bdl	bdl	0.01	0.10	0.02	0.03	98.74	Turquoise
FRAT 18	0.01	bdl	bdl	0.20	bdl	bdl	0.03	0.02	0.09	0.05	0.08	99.35	Turquoise
FRAT 19	0.02	bdl	bdl	0.11	0.01	bdl	bdl	0.02	0.25	0.04	0.01	99.03	Pale Turquoise
FRAT 20a	0.02	0.01	bdl	0.29	bdl	bdl	0.03	0.02	0.06	0.02	0.01	102.745	Turquoise
FRAT 20b	0.01	0.01	0.02	0.14	0.02	bdl	0.01	0.02	0.07	0.03	0.06	97.635	Turquoise
FRAT 21	0.02	bdl	bdl	bdl	0.02	bdl	0.01	0.01	0.01	0.02	0.09	102.08	Turquoise
FRAT 23	bdl	bdl	bdl	0.39	bdl	bdl	0.01	0.02	0.15	0.03	0.18	100.55	Turquoise ingot
FRAT 26	0.02	0.03	bdl	0.22	bdl	bdl	bdl	0.02	0.14	0.03	0.01	99.15	Turquoise lump with thick red opaque covering
FRAT 43	bdl	bdl	bdl	0.15	bdl	bdl	0.03	bdl	0.07	0.03	0.02	100.5	Translucent Turquoise
FRAT 46	bdl	bdl	bdl	0.35	bdl	bdl	0.01	bdl	0.12	bdl	0.01	101.89	Translucent Turquoise

FRAT 51	0.02	bdl	bdl	0.01	0.04	bdl	0.04	0.02	0.07	0.03	0.01	98.32	Translucent Turquoise
FRAT 52	bdl	bdl	bdl	0.10	bdl	bdl	0.04	0.02	0.07	0.03	0.05	99.34	Turquoise
FRAT 54	0.02	bdl	bdl	0.10	bdl	bdl	bdl	0.01	0.05	bdl	0.04	100.56	Translucent Turquoise
FRAT 56	0.01	bdl	bdl	0.41	bdl	bdl	bdl	bdl	0.06	0.02	0.03	99.305	Translucent Turquoise
FRAT 58a	0.04	bdl	0.03	bdl	0.08	bdl	0.08	bdl	0.07	0.03	0.02	99.92	Translucent Turquoise
FRAT 60	bdl	bdl	0.03	0.27	bdl	bdl	0.03	bdl	0.07	0.03	0.05	100.72	Translucent Turquoise
FRAT 79	0.01	bdl	bdl	0.01	0.02	bdl	bdl	bdl	0.07	bdl	0.02	100.06	Translucent Turquoise
FRAT 2b	0.02	bdl	0.27	0.03	2.87	bdl	11.57	bdl	0.02	0.22	0.90	99.845	Emerald
FRAT 8	0.01	0.01	0.01	bdl	0.03	bdl	0.01	0.02	0.12	0.03	0.11	98.75	Apple Green
FRAT 9	0.02	bdl	bdl	bdl	0.03	bdl	0.04	0.02	0.14	0.03	0.10	98.54	Apple Green
FRAT 11	0.06	bdl	0.01	0.08	0.11	bdl	0.03	0.01	0.21	0.03	0.10	98.98	Green
FRAT 12	bdl	0.03	bdl	bdl	0.02	bdl	0.04	0.02	0.15	0.03	0.06	99.92	Pale Green
FRAT 14	0.01	0.05	bdl	bdl	bdl	bdl	0.01	0.05	0.25	0.03	0.01	99.66	Opaque Green
FRAT 15	0.01	bdl	bdl	0.03	0.01	bdl	0.03	0.02	0.17	0.03	0.65	99.4	Pale green ingot
FRAT 28	0.03	bdl	0.03	bdl	bdl	bdl	0.01	bdl	0.20	0.06	0.05	100.42	Pale Green
FRAT 16	bdl	0.02	bdl	bdl	0.02	bdl	0.02	0.04	0.17	0.03	0.01	101.35	Amber Yellow
FRAT 27	bdl	bdl	0.03	0.01	0.02	bdl	0.01	0.02	0.12	0.03	0.58	100.92	Purple/pink with green edge
FRAT 58b	0.01	bdl	bdl	bdl	bdl	bdl	0.04	bdl	0.07	0.03	0.05	96.97	Opaque White
FRAT 61	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.02	0.05	0.03	0.21	97.25	Opaque White
FRAT 13	0.01	0.01	bdl	bdl	0.01	bdl	bdl	0.01	0.12	0.02	0.05	98.99	Colourless
FRAT 5	0.07	0.02	0.03	bdl	bdl	0.01	0.01	0.02	0.13	0.02	0.08	98.46	Ruby
FRAT 22	0.01	bdl	0.02	0.55	bdl	bdl	0.03	0.03	0.14	0.03	0.01	100.67	Mainly red, small area of turquoise
FRAT 55	0.03	bdl	0.06	0.18	bdl	bdl	0.01	0.03	bdl	0.03	0.09	101.06	Opaque Red
FRAT 57	0.01	bdl	0.02	0.17	bdl	bdl	bdl	0.02	0.09	bdl	0.01	99.71	Red

TABLE B

	Egyptian	Mesopotamian	Mycenaean	Uluburun
Copper	35	70	38	6
Copper Cobalt	17	44	48	2
Cobalt	22	0	25	7
Blue Total	74	114	108	15
Total	192	137	123	16
Ca:Al < 5:1	47	19	97	10
Copper	4	1	26	2
Copper Cobalt	16	16	47	2
Cobalt	20	0	24	6
Blue Total	40	17	97	10
Na:Mg > 6:1	12	1	46	10
Copper	3	1	13	2
Copper Cobalt	2	0	16	2
Cobalt	2	0	16	6
Blue Total	7	1	45	10
Ca:Al < 5:1 & Na:Mg > 6:1	7	0	42	6
Copper	1	0	10	0
Copper Cobalt	2	0	16	2
Cobalt	2	0	16	4
Blue Total	5	0	42	6

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