Glass trade on the Early Islamic Silk Road: the use of electron probe microanalysis in the investigation of glass from Pella, Jordan and Qasr al-Hayr al-Sharqi, Syria

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I hereby declare that this dissertation is all my own work, except as indicated in the text:

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Abstract:

The major and minor elemental oxide components of 49 glass samples from Pella, Jordan and 11 glass samples from Qasr al-Hayr al-Sharqi, Syria were studied using Electron Probe Microanalysis (EPMA) in order to characterise them in the context of the Early Islamic glassmaking industry. The compositional types and provenances of these glasses were determined by comparing the datasets obtained in this study to contemporary glass finds throughout the Middle East as a means of gaining insight into the production and trade of glass during this important transitional period of the Middle East. From both sites, soda-lime-silica glasses of both natron and plant ash types were discovered as well as a third miscellaneous group of unknown origin. Dated to the 9th -10th centuries CE, the findings from Pella showed that natron glass from both the Levantine coast and Egypt were being imported and potentially worked on site. Of the Qasr al-Hayr al-Sharqi glass samples dated to the 8-9th centuries CE, it was found that glass had been imported from both Egypt and the Levant as well. The plant ash glass of Qasr al-Hayr al-Sharqi was likely fused in Northern Syria, perhaps at al-Raqqa, and demonstrates one of the earliest cases of this type of glass being exported from its production zone. Plant ash glasses found at Pella were likely to have been imported from both Iraqi and Levantine primary production zones, indicating the long-distance trade occurring at the time. These findings provide a clearer image of the inter-regional trade and exchange of glass that was occurring on the Silk Road networks in the Early Islamic period as well as the greater implication of a highly diverse level of communication and interconnectedness amongst the newly united people of the Middle East.

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1. Introduction

The second half of the first millennia CE in the Middle East was a time of great transition. Following the decline of the Mediterranean-spanning Roman Empire, new powers were stepping in throughout Western Europe, taking up the mantle of rule left behind, while what remained of the Roman Empire, now Byzantium, continued to rule in the Eastern Mediterranean. Though to a relatively minor scale, frequent conflict with the neighbouring Sasanian Empire, which controlled much of the Middle East and Persia, could have resulted in a general decline of stability throughout the Eastern Mediterranean (Phelps 2017, 46–58; Whittow 2010). This steady decline and likely many other factors could have driven the 7th century CE Islamic conquest from the Arabian Peninsula northwards, towards the Byzantine and Sasanian Empires that dominated the Middle East at the time (Altaweel & Squitieri 2018, 48–52; Büntgen *et al.* 2016; Phelps 2017, 46–58). The swift and dramatic change in rulership of the Middle East affected many aspects of society culturally, economically and politically, though in some ways, this new rule made little immediate impact (Cobb 2010; Phelps 2017, 46–58). While the power structures in the administration over much of these lands had changed hands, a great amount of everyday life remained unaffected (Barfod *et al.* 2018; Cobb 2010; Phelps *et al.* 2016). The uniting of these lands actually may have benefitted many people due to the new connection between once distant societies for trade and cultural exchange. The material culture of lands once ruled by the Sasanians and Byzantines remained much the same, with designs and practices seeing no change from what was done before (Barfod *et al.* 2018; Cobb 2010; Freestone *et al.* 2002; 2002; Gordon 2009; Phelps *et al.* 2016; Rehren & Freestone 2015).

As the Byzantines had continued a similar glass production model as that of the Romans before them (Freestone *et al.* 2002), the new Islamic caliphate saw a similar continuation following the Byzantines, making little immediate impact on glass production in the Middle East (Phelps *et al.* 2016). Large amounts of mineral soda such as natron would be imported from Egypt and then melted with sand to produce slabs of glass in large tank furnaces at primary production sites on the Levantine coast such as those in Apollonia, Bet Eli'ezer and Bet She'arim (Freestone *et al.* 2008; Gorin-Rosen 2000; Henderson 2013, 280–82). These would then be broken up into small chunks and exported to various secondary glass production sites throughout the Levant and Egypt in order to be shaped and coloured into useable vessels and decoration (Freestone *et al.* 2002; Phelps *et al.* 2016; Rehren & Freestone 2015). The eventual decline of mineral soda usage would be evident in the Middle East by the 8th century CE and a new source of soda would be rediscovered: plant ash from soda-rich halophytic plants. Originally used in the Bronze Age to fuse glass, plant ash glass primary production sites would spring up throughout Mesopotamia and Northern Syria, eventually replacing natron use all together in the Middle East (Freestone 2006; Phelps *et al.* 2016; Rehren & Freestone 2015; Shortland *et al.* 2006). Furthermore, the mode of glass production in the Middle East would change. Many urban hubs throughout the

Islamic caliphate would begin to house both primary and secondary glass workshops, catering for both local usage and exported trade (Henderson *et al.* 2016).

Since at least 1961, scientific analysis has been used to characterise glass in groups respective to their chemical compositions (Sayre & Smith 1961). The compositions of ancient glass can be reflective of the technology used to make them, the provenance of the raw materials, and the trade in which they could have been part of. Impurities introduced by raw materials can give an indication of what kinds of materials were used such as plant ashes or natron and where they may have originated from. One can even determine the secondary processes in production such as colouration and the extent to which glass has been remelted and reused (Freestone 2015; Henderson *et al.* 2009; 2016; Phelps *et al.* 2016; Rehren & Freestone 2015).

From the Early Islamic Middle East many glass compositional groups have been identified (Ceglia *et al.* 2015; Freestone *et al.* 2000; Gratuze & Barrandon 1990; Henderson 2003; Phelps *et al.* 2016; Rehren & Freestone 2015; Sayre & Smith 1961). Related to the geochemistry of silica and soda sources, groups attributed to regional production zones of both natron and plant ash glasses can be compared to new archaeological glass finds in order to determine their origins and gain insight into how they may have travelled and been worked (Henderson 2013, 83–126). Both of the soda-lime-silica type, plant ash and natron glasses can be further split by their chemical compositions relating to where in the Middle East they were produced (Freestone *et al.* 2002). Due to the prevalence of inter-regional trade along the Silk Road in the Early Islamic period it is valuable to be able to determine how glass moved within it (Gordon 2009, 39–46). The flow of people travelling along the Silk Road would bring new ideas, culture and technology reflected in the material culture of artifacts they carried (Foltz 1999). The analysis of such glass within these routes can therefore further define the ancient inter-regional dialogues occurring at that time (Henderson 2013, 276–78).

This research uses electron probe microanalysis (EMPA) to present the major and minor element compositions of glass assemblages from two geographically significant sites in the context of the Silk Road in order to determine how the cultural, economic, social, political and technological transitions in the Early Islamic period may have been reflected in the trade and production of glass. Therefore, perhaps painting a clearer image of life under Early Islamic rule in the Middle East and specifically in the Syrian and Levantine regions. The first of these sites is Qasr al-Hayr al-Sharqi in Syria, a desert castle located on an ancient route in the Syrian desert between Mesopotamia and the Levant. The second is Pella in Jordan, an ancient city located on the eastern bank of the Jordan Valley and near one of the major ancient roads leading out of Palestine and to the east.

1.1. Research questions

- Can the major and minor element analysis of glass fragments from Qasr al-Hayr al-Sharqi, Syria and Pella, Jordan specify the technologies and production models used to produce them?
- Can the major and minor element analysis of glass fragments from Qasr al-Hayr al-Sharqi, Syria and Pella, Jordan indicate their provenance and the extent to which they were traded?
- Can the major and minor element analysis of glass fragments from Qasr al-Hayr al-Sharqi, Syria and Pella, Jordan find evidence of recycling?
- How do the elemental compositions of glass fragments from Qasr al-Hayr al-Sharqi, Syria and Pella, Jordan reflect the wider cultural, economic, social and political contexts of these sites on the Silk Road in the Early Islamic period?

2. Background and related work

2.1. Defining glass compositions

The composition of ancient glasses are most commonly defined by their major element oxides, obtained from the different raw materials used to produce them. In the Middle East the type of glass normally found is of the soda-lime-silica type where the soda corresponds to sodium oxide (Na_2O), lime relating to calcium oxide (CaO) and silica being silicon dioxide (SiO_2). The raw materials used in the production of this type of glass would introduce these as well as many other oxides. Typically, glass would be made from the process of melting sand or quartz pebbles in the presence of specifically soda-rich additions such as certain minerals or halophytic plant ashes like those in the *Chenopodiaceae* family, native to the Middle East. The addition of soda-rich material would act as a flux or network modifier, lowering the melting temperature of sand to that capable of being achieved in furnaces at the time (Karmakar 2016). The lime component of the glass would also be added from plant ashes or perhaps other sources such as seashell fragments (Barkoudah & Henderson 2006). The lime would act as a network stabiliser playing an important role in preventing decomposition thus improving its durability from weathering (Hasanuzzaman *et al.* 2016).

While still being of the soda-lime-silica type, these are not the only components usually found in ancient glasses. Impurities within the raw materials, as well as deliberately added inclusions, would also play a part in the overall compositions. For example, plant ashes that would have been used as a flux would introduce other oxide elements such as that of potassium (K_2O) or magnesium (MgO) (Shortland *et al.* 2006). As well as this, materials would be added in order to deliberately change the glass colour and opacity. Copper-rich minerals such as malachite may have been added to produce a turquoise colour as well as manganese-rich materials like pyrolusite to remove unwanted colour from ‘raw’ glass (raw glass in this case means glass unintentionally coloured by deliberate inclusions) (Henderson, 2013, 75). The conditions within the furnace would also affect the composition of glass. When done intentionally, the furnace conditions would be carefully manipulated in order to change a certain quality of the glass. For example, an effort to control the time that the glass remains in the furnace can determine the oxidation state of elements in the glass, such as the presence of iron oxide varying from a red to a green colour (Schreurs & Brill 1984). Some of the earliest appearances of glass in the archaeological record seem to have been deliberately coloured in order to imitate precious stones and minerals such as turquoise and lapis lazuli. An example of this can be seen in the Amarna letters which were dated to the 14th Century BCE and found in Egypt (Duckworth 2011, 86–88). These consisted of details of a trade agreement between the Egyptian kingdom and its Levantine neighbours, listing lapis lazuli "from the mountain" and "from the kiln" amongst other precious stones and metals. This may indicate the perceived high value of coloured glass which would have been skilfully produced "from the kiln" compared to its likeness obtained "from the mountain" (Duckworth 2011, 86–88; Shortland & Tite 2000). For most of its existence from the Bronze Age to antiquity, glassmaking was mostly reserved for the elite in society, kept as a specialised secret skill and controlled by the royalty of the time (Freestone *et al.* 2008).

2.2. Glassmaking before the Arab conquests

2.2.1. Roman and Byzantine glass

Glass was first mass produced in the 1st century CE by the Romans, mostly consisting of the natron type, hundreds of years before the Islamic rulership of the Middle East. The adoption of glassblowing technology resulted in a rapid and widespread usage of glass vessels in all strata of society. Glassblowing had made what was once the slow and expensive process of glass working, almost primarily associated with the societal elite, into a more readily available practice, creating many vessels as just a means to transport trade commodities. Glass bottles, shaped square for packing efficiency, were used to transport more valuable goods such as olive oil and wine (Charlesworth 1966). This is not to say that glass lost its value entirely in Roman society; older methods of glassmaking such as core forming were still used, albeit still a slower and more costly process thus limiting its production and increasing its worth (Prior 2015). An example of a rarer and more impressive use of glassmaking is the Lycurgus Cup, indicating a highly sophisticated level of craftmanship that no doubt would have been valued highly and perhaps reserved for special usage (Freestone *et al.* 2007). Roman usage of heavily coloured glass was also widely used in their tesserae. Most likely produced in local specialised workshops by using colouring and opacifying salts mixed with imported glass, tesserae would be used as decoration for wealthy households and important public buildings (Basso *et al.* 2014).

The Roman production of glass can be described as a centralised model, meaning that it would be fused at "primary" production centres in a small region of the Empire and then distributed to "secondary" production centres throughout for re-melting and local craft usage. A simplified example of this can be seen in Figure 1. Although historical evidence such as Pliny the Elder's writing on glassmaking suggests that glass was fused all over Europe under the Roman Empire, there is very little archaeological evidence to support this other than that in the Eastern Mediterranean (Gorin-Rosen 2000). The chemical compositions of Roman glasses made in the Empire are so homogenous that it is likely that they were all produced using similar raw materials from one region. Most evidence suggests that the glass would have been produced on the Levantine coast and in Egypt, where there would have been both plenty of usable sand as well as nearby access to the sodium-rich salt deposits of Egypt. One such example of the salt flats used was located at Wadi el Natrun, hence the name of the natron type of glass typically produced by the Romans (Stern 1999). Archaeological evidence of primary glassmaking in these regions can be seen in a number of sites in these areas, including later, large tank furnaces capable of holding up to nine tonnes of glass, thus showing the extent of the large scale industry in its production (Gorin-Rosen 2000; Nenna 2015).

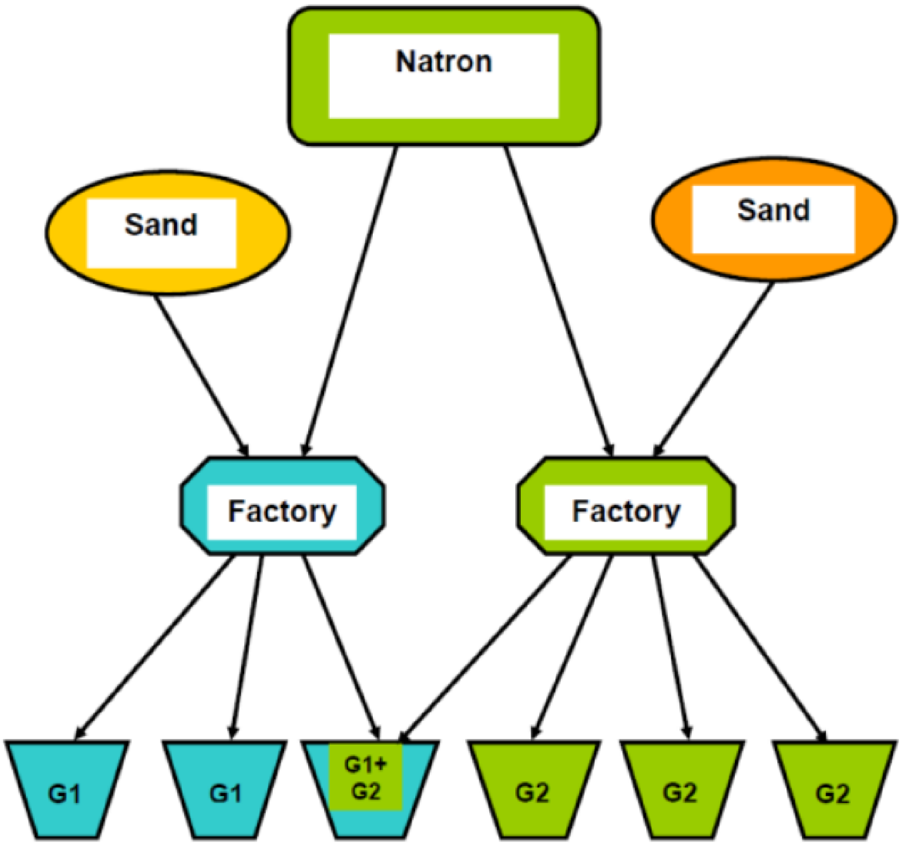

Figure 1: Diagram outlining a centralised production model of glass. Obtained from Phelps (2017)

After the collapse of the Western Roman Empire, evidence suggests that there was a continuation of the glass industry in what became the Byzantine Empire. Large-scale primary production seemingly flourished with new primary production centres appearing along the Levantine coast (Stern 1999). If not reduced somewhat, there was a continuation of trade throughout the Mediterranean to secondary glass production sites where early medieval glassworkers would still be able to produce a wide range of colours using similar technology as the Romans had previously (Ricciardi *et al.* 2009). Such a highly skilled craft would likely have remained tightly controlled with select groups being responsible for glass making and working in the Eastern Mediterranean, perhaps due to the difficulty of production or value in the trade networks of the time. The Byzantines also continued to widely use glass mosaics as decoration, as well as utilising techniques like gold sandwiching, producing an almost uniquely “Byzantine” style (James 2006). This method of decorating glass involved the encasing of thin gold sheets between two layers of glass in a process that only the most skilled glassworkers of the time could have carried out well (Wenzel 1988). Scientific analysis of glass from this time also suggested that perhaps the production model used to describe the later antique distribution and working of glass became less centralised; newer and more varied glass compositions were being traded and mixed, thus indicating that more regional-specific technologies and raw materials were being used (James 2006; Whitehouse 2008). Analysis carried out by Ceglia et al. (2015) and Freestone et al. (2002) as well as others (Gratuze & Barrandon 1990; Mirti *et al.* 1993; Neri *et al.* 2016) have shown that in late antiquity there were multiple different compositional groups as well as potential evidence for mixing between them, perhaps indicating a more decentralised model where raw materials such as sands would have differed from one production zone to another. Although the use of Egyptian natron appears to still be imported in order to be used as a flux for most Mediterranean glasses.

The reuse and recycling of glass can be seen throughout the Roman era (Brems & Degryse 2014). The act of just remelting glass from primary production centres showed that it was a widely accepted practice, with evidence indicating that broken vessels and windows would still be valuable to the secondary glass workshops in addition to the ‘raw’ imported glass from the Middle East and Egypt (Stern 1999). Although impurities would be introduced to glass during the initial fusing procedure, repeated remelting would most likely introduce further unwanted additions to a noticeable degree (Henderson 2013, 333–34; Jackson & Paynter 2016). Perhaps unwanted colours would arise or there would be even greater difficulty in the shaping process, resulting in unworkable glass (Freestone 2006). While most Roman glass was already weakly coloured blue-green by iron oxides originating from sand, steps would be taken in the glass production process to remove this quality. For example, additions of decolourisers like manganese and antinomy oxides could be seen in glass compositions found at secondary workshops, perhaps even originating from designated workshops specialising in this process of decolourising and colouring (Freestone 2015). While likely more common in the regions further west from Middle Eastern primary production centres, recycling was also seen in Levantine regions throughout Roman rule. There is evidence that even the use of glass differed depending on the degree that glass had been recycled; less compositionally pure glass would be used to make coloured tesserae. This would likely be acceptable as natural colouration from these impurities would not need to be considered so much when a stronger colouriser is added (Schibille *et al.* 2012).

2.2.2. Sasanian glassmaking

Further east from the Mediterranean during the Byzantine period we can see similar modes of glass production in Sasanian ruled land. Although the Sasanian glass industry is in need of greater study, there is evidence of controlled production zones where there would be both mass production and rarer, specialised production (Simpson 2014). Unique technologies and stylistic developments are seen in the Sasanian glassmaking industry where artisans throughout the empire would be experimenting with techniques like cutting which would appear to be highly coveted throughout Western and Central Asia (Mirti *et al.* 2009). Contrasting to the eastern Mediterranean traditions of glassmaking, where instead of using mineral soda as a flux for their glass, the Sasanians would use local halophytic plant ashes, which were likely easier to obtain than Egyptian natron (Rehren & Freestone 2015). As well as this, the presence of Roman and Byzantine glasses found throughout the boundaries of the Sasanian Empire, show a degree of inter-connectedness where perhaps an exchange of ideas and practices occurred (Henderson *et al.* 2004; Simpson 2014).

2.3. Glassmaking under Islamic rule

2.3.1. Overview of the Early Islamic World

In the 7th century CE the Middle East saw vast change. Under Mohammed and his followers' conquests of the Arabian Peninsula, the Muslims looked north for greater expansion of Islamic rule. After his death in 632 CE, Mohammed's descendants and successors consolidated Islamic rule under one caliphate, initially ruled by Abu Bakr, the first of the Rashidun caliphs (rightly guided descendants of the messenger of God) (Sowerwine, 2010, 5). The following conquests of the Rashidun resulted in much of the Middle East falling under Islamic control. At the end of the reign of the last Rashidun Caliph, Hasan ibn Ali, in 661 CE the caliphate occupied lands including Syria, the Levant, the southern Caucasus and much of Persia and Egypt. This resulted in the collapse of the Sasanian Empire as well as the permanent weakening of Byzantine control of the Mediterranean. Following this, the caliphate was held by different dynasties over time. The first of these dynasties were the Umayyads, who would expand the domain of the caliphate. By the mid-8th Century CE Umayyad control would stretch from the majority of the Iberian Peninsula to modern day Pakistan, including much of Central Asia up to cities such as Tashkent and Samarkand (Gordon, 2009, 29). Culturally, the Umayyad Empire showed a lot of regional continuation from its pre-Islamic rulers; much of the technology and practices of those before saw minimal change. Little difference in Umayyad art and architecture from the likes of the Byzantines and Sasanians perhaps showed an effort to establish Islamic legitimacy in the newly conquered regions (McNicoll & Walmsley 1982). Historical evidence even suggests that the Umayyads employed Byzantine and Sasanian artisans to assist in the building and decoration of large projects such as the Great Mosque of Damascus and various other buildings and fortifications throughout Syria and the Levant. An example of these displays of wealth and power are the newly constructed desert castles built in the Byzantine style (Eger 2012; Finster & Schmidt 2005). We also see a shift in the centralisation of government under the Umayyads; the first Umayyad caliph Mu'awiyah I moved the capital of the Empire to Damascus thus bringing its focus to the Middle East. Although there was little direct local change from the conquest, it is also evident that the way people were living in the Middle East had been slowly changing somewhat in the previous centuries; gradual differences in settlement structure showed more ruralisation of towns and the decline of infrastructure, perhaps caused by local political instability, plague or even varying climate from the 5th century CE onwards (Sigl *et al.* 2015). While these factors may have made it easier for the Islamic conquerors of the Middle East to take over, there is little evidence of immediate change in the everyday lives of those living in these territories (Phelps *et al.* 2016). What change we do see would most likely have stemmed from the natural shifts in society following from what was seen already (Magness 2003, 75–92). It is likely that Umayyad rule may have influenced society more subtly; while still being allowed to continue uninterrupted, the non-Muslims would have been incentivised to convert through the selective tax policies imposed. Over time, the demands of the Islamic elite and increased centralisation of the production of crafts may have resulted in almost proto-Islamic technologies and styles (Henderson, 2013, 252–257; Phelps et al., 2016; Phelps, 2017, 49–54).

Over time, however, Islam showed signs of fracture: different sects and political powers would claim the title of caliph, eventually resulting in the division of the Umayyad Caliphate. Next to rule the caliphate was the Abbasid dynasty from 750 CE followed by what is said to be the peak of Islamic control and centralisation in the Middle East. Although, eventually, rule would be diminished and by the 10th century CE, multiple Islamic states would exist in the Middle East with caliphates claimed by dynasties such as the Fatimids and Ayyubids. Centres of power would continue to move throughout the Islamic rule of the Middle East. Caliph Al-Mansur, one of the first Abbasid caliphs, would bring the capital further east to Iraq, founding cities like Baghdad and Samarra to act as new central hubs for politics, commerce and art, rivalling the like of those such as Constantinople and Rome (Henderson 2013, 252–57). It is evident that the Persians and the Sasanian Empire were viewed quite highly in the Abbasid Caliphate with much of their society continuing under Islamic rule. Persian administrators and scholars would be held to great esteem, evident when earlier Abbasid caliphs would incorporate Sasanian traditions into many aspects of their caliphate (Yāršātir 1998). While perhaps in an effort to bring the focus of the caliphate closer to the old Sasanian heartland, where once its capital of Ctesiphon stood not far down the Tigris River, Baghdad would soon be seen as a new and uniquely Islamic centre of the caliphate. The centralisation of Islamic control with efforts made by various caliphs began what is called the "Islamic Golden Age" (Gordon 2009, 22–23; Phelps 2017, 54–57). With the likes of Caliph Harun al-Rashid and al-Ma'mum, every aspect of society was supported: ranging from scholarly practices like medicine and astronomy to the arts and their industries such as metal working and, of course, glass working (Kennedy 2015, 107–35). With the caliphal rule encompassing such a vast area of land, groups of artisans and scholars could be brought in from great distances and have their ideas and practices shared and mixed thus forming a more unique “Islamic” culture (Kennedy 2015, 107–35). The existence of the House of Wisdom shows how important a centre of learning Baghdad would become, with scholars invited from regions beyond the caliphate itself to question and develop all aspects of society. As well as this, the emergence of large bazaars showed the scope of this intermixing in other aspects of society including the artistic and agricultural practices (Foltz 1999, 89–109; Kennedy 2015, 115–16). In many major cities during the Abbasid Caliphate we can also see the formation of dedicated craft zones with even further innovations in the arts such as pottery, metal and glass working (Henderson *et al.* 2004). With this widespread Abbasid control this trade and movement would have flourished on the Silk Road, making it easier than ever for the spread of ideas and goods in the Middle East and beyond (Gordon 2009, 39–46; Henderson 2013, 252–66).

2.3.2. Early Islamic glassmaking

This concentration and centralisation of industrial and artistic practices is reflected in the changes in glassmaking and working throughout the early Islamic period. For example, following the conquest, glass produced in once Sasanian and Byzantine territory would show very similar regional designs and decoration as seen as previously, thus, indicating this continuity of production in Byzantine and Sasanian glasshouses (Mirti *et al.* 2009; Whitehouse 2008). Furthermore, there is little archaeological evidence for destruction or abrupt change in settlement structure at known glass working sites in the Levant, perhaps suggesting that life remained relatively unchanged for its occupants (Phelps *et al.* 2016). This is also reflected in compositional analyses of glasses produced during the Islamic transition. Glass produced on the Levantine coast previously by the Byzantines continued to use natron and follow a similar production model as before (Barfod *et al.* 2018; Rehren & Freestone 2015). Compositional groups as described by many seem to have continued to be produced from sites in both Egypt and the Levant. As well as this, the reuse of older, Byzantine glass was also seen, perhaps even worked separately from newer glass, showing a degree of understanding and differentiation in the “quality” of the product (Ceglia *et al.* 2015; Fiorentino *et al.* 2018; Freestone *et al.* 2008; 2015; Phelps *et al.* 2016). We also see that the presence of what seems to be designated workshops for the specific colouration of glass may have continued, where glasses of specific compositions appear to have relatively similar colouration, maybe due to the similarity of materials and procedures (Fiorentino *et al.* 2018; Freestone *et al.* 2018). We do, however, see a reduction in primary Levantine glass during the Umayyad period at the same time as an increase in imported Egyptian glass as well as increased recycling of previously used glass and cullet. This may be indicative of a shifting of the industry and Mediterranean trade under the new Islamic rule as well as perhaps a reduction in the supply of Egyptian natron for fusion. This may have been due to the fact that natron supplies were running out and as a response, those in charge of distribution in Egypt kept it under tighter control or even that trade of natron became less viable in a more unpredictable Eastern Mediterranean (Phelps *et al.* 2016). Despite this, we do see the construction of new glass workshops in the Levant during the Early Islamic period, suggesting a continuing growth of the glass working industry (Freestone 2006). Sites such as Bet Eli'ezer in Palestine would produce vast amounts of glass in tank furnaces with the intention of being shipped out to secondary glass workshops (Gorin-Rosen 2000). While at the same time Palestinian coastal sites such as those near Apollonia appear to be have been abandoned in favour of those more inland, perhaps driven by the increasing difficulty of trade (Walmsley 2012). This can also be seen in the chemical compositions of glasses produced from these sites; lower soda levels in Bet Eli'ezer glass would have resulted in a product that was more difficult to work and may have been seen as a lower quality product (Phelps *et al.* 2016). This may also be the result of increased trade inland, encouraged by the new Islamic dominance of the Middle East; secondary glass workshops containing natron glass start to be seen in Jordan and Syria, maybe indicative of the increased centralisation brought by the caliphs (Barfod et al., 2018; Greiff and Keller, 2014; Henderson, 2013, 290–296; O'Hea, 2018). Furthermore, Freestone (2020) suggests that there may have been competition between Egyptian and Levantine glassmakers, even to a degree that Egyptians deliberately coloured their raw glass to differentiate it from their "opposition" in the Levant (Freestone *et al.* 2018). Additionally, we see the usage of glass in Umayyad settlements further East in buildings such as their new desert castles (Adlington *et al.* 2020; Fiorentino *et al.* 2018). The similarity to Byzantine glass usage and decoration such as that of tesserae in Umayyad constructions further indicates the continuation of glass working traditions and it is likely that Byzantine artisans were used to assist in their application (Henderson, 2013, 270–282). This may suggest that in early Islamic society glass may have been seen more as a "foreign" material. Indeed, alongside the Christian Byzantines, there were groups of Jewish glassworkers (perhaps paired with silversmiths) and it is likely that they had been part of the industry under Byzantine rule as well (Goitein, 1999, 225). The lack of Umayyad inscriptions on glass produced at this time suggests that there was little Islamic patronage or control over the industry (Henderson, 2013, 260). Furthermore, under the Umayyads, Sasanian glass production seemingly had ceased in Persia and Iraq. Despite this and the fact that it did not seem as prevalent as natron glass, perhaps due to the Umayyad centre of focus being in the Levant, it is unlikely that it was forgotten and could have been a pre-cursor inspiration for the uniquely Islamic glass seen later on (Henderson, 2013, 260–261; Mirti et al., 2008). As the Umayyad period came to an end, we would also begin to see a large shift in the glassmaking industry in the Middle East.

2.3.3. The decline of natron glass

The use of natron glass types declined in the Middle East from the 8th century CE until eventually almost being completely eclipsed by plant ash glass by the 10th century CE (Freestone 2015; Phelps *et al.* 2016; Schibille 2011; Schibille *et al.* 2019; Shortland *et al.* 2006). Instead, we see this widespread adoption of plant ash glass throughout the Islamic Empire during Abbasid rule (Henderson 2013, 97–101). Why natron glass production had appeared to cease is unknown for certain. It is speculated that one reason may have been the diminishing supply of mineral soda from the salt flats of Egypt such as that from Wadi el

Natrun (Picon *et al.* 2008). It is noted that while production of natron glass had effectively stopped in the Levant by the 9th and 10th centuries CE, natron deposits may have continued to be exploited in Egypt for a further two or three centuries, perhaps indicating that there was tighter control of its export as a result of its depletion (Henderson, 2013, 282–290; Schibille et al., 2019; Shortland et al., 2006). The rise of the use of plant ash is likely to have been a result of glassmakers searching for other sources of soda. Due to the expanse of the caliphate at this time, it may be no surprise that techniques would have been borrowed and adapted from both the Sasanian and Byzantine glassmaking technologies, especially seeing the reverence of the Persians by the new Arab leadership as mentioned previously as well as previous replication of Byzantine practices in Umayyad works. Moving the centres of Islamic control to places such as Baghdad could explain the similarities of Early Abbasid glass decoration to Sasanian techniques as seen previously in the very same region a century or so before (Walmsley 2013, 54–58). Although there is no evidence of Sasanian glass produced since the Islamic conquests and never to the scale that at which the Abbasids produced it, it is unlikely the practice was completely forgotten (Henderson, 2013, 265–266). The large-scale industry brought to the lands at this time could be seen as a sort of "re-invention" of the practice, especially following the dwindling occurrence of natron types seen during the Umayyad period. This new process of glass fusion remained to produce soda-lime-silica glass but now the soda source was obtained from plant ashes of local halophytic plants as described previously. The lime source is likely to have been obtained from the plant ashes and it is likely that especially calcium-rich variants were picked to be ashed. Perhaps even bone fragments and calcium-rich feldspars were used as an additional calcium source. The silica source would have been sands easily available to production centres, and most likely especially pure sands would have been chosen as well as those with calcium-rich minerals like some feldspars (Henderson, 2013, 282–290). As well as this, crushed quartz pebbles may have been chosen as a relatively pure silica source. This material could have been obtained from the banks of the Euphrates and Tigris rivers after being transported from the Anatolian mountains where many known production centres lay (Henderson, 2013, 263–264; Henderson et al., 2016; Schibille et al., 2018). These techniques were likely to have been seen in many production centres around the caliphate with mass production occurring at a scale comparable to the Romans, if not now produced in a much more widespread geographic area. Although production of large volumes of glass in tank furnaces would more likely result in more man-hours than natron glass, where the volume of plants gathered would be much greater for the same amount of soda provided by mineral sources, it would have been a necessity to change once access to fresh natron diminished. Though, innovations helped lead to the lower melting points of Islamic glasses compared to natron types, therefore reducing the volume of fuel needed in the process, a large amount of control and support would have been needed to organise the largescale gathering and supply to Islamic workshops (Henderson 2002). With caliphs like Harun al-Rashid and his son Al-Ma'mun who were known to have supported a wide range of industries and crafts from all over the Empire, there could have been encouragement of local craftsmen to practice in these industries and perhaps continue what was known to them and had been passed down from previous generations. Although under Caliph Harun al-Rashid, the capital was moved to al-Raqqa in Syria which contrasts somewhat to the Persian focal centre determined by other Abbasid caliphs such as Baghdad and Samarra. There, however, we still see the new shifts in society that promoted a uniquely “Islamic” identity. Henderson (2013, 257–278) explains that artisans from all over the caliphate would have been invited and congregated in this new capital’s industrial zone, resulting in the and spread and sharing of practices of the glassmakers of both Persia and the Levant. This intermixing of cultures and practices perhaps resulted in the increased levels of innovation seen during this time and not just in al-Raqqa but Samarra and Baghdad too. Certainly, what was becoming “Islamic” types of glasses appears to be greatly influenced by Sasanian and Byzantine traditions. Furthermore, perhaps there was a push from this caliph to make these arts and crafts their own as “a means of belonging to a Muslim society” (Henderson, 2013, 266). No doubt the emergence of an industrial complex seen in al-Raqqa, similar to that seen in centres such as Baghdad and Samarra, showed the emerging ownership of crafts like glass working as something Islamic rather than just done by “foreign” craftsmen.

2.4. The World of Islamic glass

2.4.1. Islamic glass production

As studied by Henderson (1999), al-Raqqa is the only known inland site in the Middle East that shows evidence of primary glassmaking. In workshops at al-Raqqa we can see a level of experimentation and innovation that perhaps gives evidence of this mixing of practices by artisans from all over. Henderson (1999) found four distinct glass groups in al-Raqqa, produced over many centuries throughout its occupation. From here we also see a more compositionally consistent type of Islamic glass that became a standard from the Early Islamic period onwards. There were some glasses of natron type, likely worked near the beginning of its founding when natron was still being produced, but it did not see much mixing with plant ash types, perhaps differentiating these types by purpose and/or workability. The experimentation we see at al-Raqqa could be indicative of the mixing of different cultures and practices, perhaps showing the process of innovation occurring in the early Abbasid period where different combinations of traditions and technologies would have been tried and tested for potential use (Henderson *et al.* 2005). We also see interactions between the industries at these industrial centres of this type. We know that the same plant ashes were used to make soap which could have had specialised jobs required to harvest and prepare such material, and the collection of fuel to supply kilns in ceramic and glass workshops would have been instrumental for such a large industrial complex. There may have even been interaction with animal agriculture in order to obtain bones fragments. Great levels of organisation would be needed in order to coordinate all the practices to such a degree. Large amounts of Raqqa type glasses have not been found in many other places, however. This may be due to the lack of glass archaeology focused on the Islamic Middle East and perhaps that the usage of such glass from this production centre was primarily used in local contexts. What has been found of the Raqqa type elsewhere appears to be of vessels with consistent decoration to other Raqqa glasses. Due to this and analysis carried out by Henderson et al. (2016) it seems that glass would have been worked locally after being fused, perhaps in workshops in the same industrial centre. In addition, this practice of local specialisation of both primary and secondary glass working existed at other cosmopolitan hubs throughout the caliphate with significant regional variations (Schibille *et al.* 2018). Centres as close as Samarra and Ctesiphon had significant differences in their glasses, but they also contained similarities that contrast to other regions such as the Levant and Northern Syria. These similarities and differences indicate a kind of decentralised production model of Islamic plant ash glasses; broad regional production of glass in the Levant, Syria and Iran/Iraq would have contained smaller sub-regions with glass produced independently in "cosmopolitan hubs". While glass would have remained near to their creation, some trade would have occurred between these hubs, perhaps due to demand for glass types produced in other regions. Specialisations of types and decorations can be seen in these regions; for example, trail decorations may have been more uniquely Levantine and colourless cut glass more prominent in Iran and Iraq (Henderson *et al.* 2016). This contrasts greatly to the previously seen Umayyad and Byzantine production models where glass cullet would have been transported to secondary glass workshops elsewhere to be shaped and moulded for use. Specialisations would perhaps have been introduced at these secondary workshop locations instead. This is not to say that there was not intermixing of these glass types; it was found by Henderson *et al.* (2016) that some glass decorated and worked in Ctesiphon in Iraq would have likely been fused in the Levant, suggesting it was perhaps a more complex relationship between glass working zones than simply decentralised. Phelps (2018), however, also indicates that Islamic glass production in the Levant during Abbasid rule could have been different from the rest of the Islamic glassmaking industry at the time. With evidence described by Henderson (2013, 358), including that which was found on the Serçe Limanı, we know that glass cullet was being traded throughout the Mediterranean to be worked in places such as Venice. Also, it appears that some glass would have been sent to places in the Levant, such as Ramla in modern day Israel, for secondary production (Phelps 2018). It is argued that because there has been no evidence of secondary workshops at Tyre and the tank furnaces used for production were at too large a scale for local production, a centralised model was being followed (Phelps 2018). This shows some similarity to the ways in which glass was worked in the Levant previously when natron was being used (Phelps *et al.* 2016; Rehren & Freestone 2015). While Tyre was unlikely to be the only primary production centre in the Levant perhaps a semi-centralised model was seen similar to the Byzantine and Umayyad times. The lack of evidence, however, does not ensure that this is a good model for the glass industry in the Levant at the time therefore more analysis must be carried out in order to gauge more firmly how glass travelled in this region. While primary and secondary production may have been occurring in sites such as Tyre and Beirut, it is hard to tell the extent of production on the Levantine coast without direct evidence of glass fusion. However, if it had been produced at these sites, it is probable that it would have been traded locally as well as to secondary glass working sites such as Ramla (Henderson *et al.* 2016; Phelps 2018).

2.4.2. Islamic glass trade

The Islamic conquest of the Middle East had brought a greater freedom of travel within the caliphate. As mentioned previously the exchange of ideas and people was actively encouraged by the likes of Caliph Harun al-Rashid and aided with a large empire to maintain order and control, trade had flourished. Evidence of this can be seen by the apparent increase of movement of objects found throughout; even the movement of people can be seen through the spread of Islam to the fringes of the caliphate and beyond (Foltz, 1999, 89–109). This network of trade routes would have been part of the Silk Road. Figure 2 shows the network-like structure and complexity of the routes within the Silk Road and other associated trade routes. While many other materials would have travelled within it, including glass, it would have allowed interaction between cultures spanning from Japan to as far as Scandinavian Sweden (Abe *et al.* 2018; Gyllensvärd 2004; Loveluck 2013, 309). Early Islamic glass even found its way to the Chinese Famen Temple in Shanxi Province, likely travelling a great distance to reach there (Henderson, 2013, 358–7). Infrastructure would have been built in settlements along the Silk Road to accommodate the movement of merchants and travellers. Caravanserais would have housed such people temporarily, acting as a place of respite and enabling trade between those who occupied them (Henderson *et al.* 2005; Nossov 2013; Walmsley 2008). Furthermore, there was a thriving mercantile economy occurring at the same time known as the Maritime Silk Road that was mostly taking place in the Indian Ocean, allowing for an even greater exchange of goods (Swan *et al.* 2017). Settlements near these trade routes would have likely benefited greatly from the movement of wealth as well as the exchange of ideas, perhaps resulting in the technological innovation as mentioned previously as well as the economic boom seen in Islamic centres of control such as al-Raqqa, Samarra and Baghdad. This as well as likely other factors explains the large-scale increase of glass production seen in the Islamic Middle East as well as the beginning of what is known as the “Islamic Golden Age”. Moreover, this large-scale movement of goods would no doubt include the transit of glass. The high-level specialisation required to produce glass would indicate how much of a luxury material it was, coveted by those who could afford it, especially in regions far from its production (Jiayao 2002).

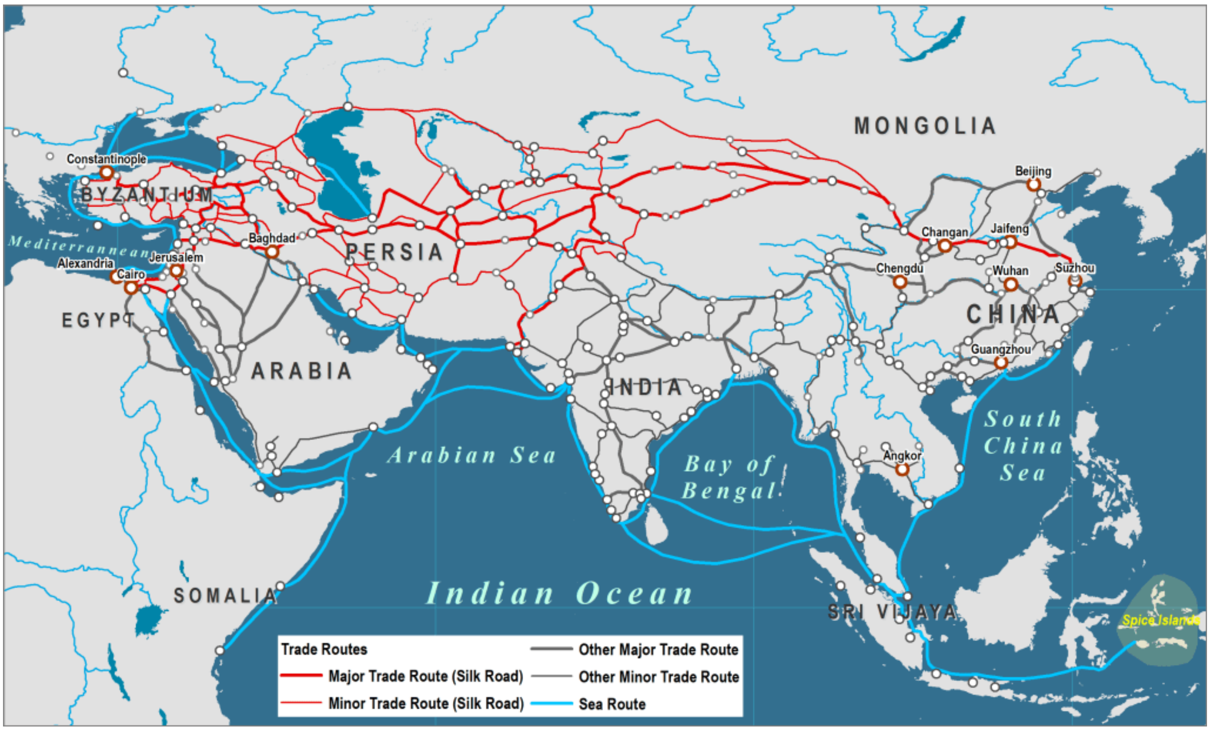

Figure 2: map of Asia depicting some of the major trade routes within the Silk Road and beyond. Image from: https://transportgeography.org/?page_id=1048 Accessed: 24/07/2020

2.5. Scientific analysis of ancient glass

The scientific analysis of glass can be used to uncover a large amount of information about the technology used to produce it as well as the materials used to make them; where it came from and how it may have been worked; and also perhaps the relationship that the people in the past had with the material. The variation in chemical compositions of ancient glasses could perhaps reflect regional differences in the raw materials used in the fusion process as well as in the secondary stage of glass working. This includes what would have been used to colour the glass, where the colourants came from and also to what extent recycling and reuse were part of the process (Henderson, 2013, 83–126). Impurities in the raw materials used to fuse glass may be unique to the geographical area in which they came from. Deriving from silica sources such as sand, for example, one could find minor or trace amounts of alumina (Al_2O_3), calcium oxide (CaO), chromium (Cr), iron oxides (FeO), titanium oxide (TiO_2) and magnesia (MgO) in glass compositions. Some of these may have been introduced intentionally or unintentionally, perhaps in an attempt to colour the glass or improve its workability. Feldspars, shells and bone fragments may have been added in order to increase lime levels that may not have been sufficient from just the sands or quartz pebbles used in the fusion process (Henderson, 2013, 65, 2003; Henderson et al., 2016; Phelps, 2018; Phelps et al., 2016; Schibille et al., 2018, 2016). Glasses fluxed using plant ashes would likely have impurities derived from the plants used. Many factors would determine the chemical composition of these ashes, including the species of plant, the geochemistry of the land they grew on and the process in which they were ashed. It is likely that certain plants would have been chosen for their soda quantities as well as perhaps lime content, while also impurities such as magnesium (MgO) and potassium (K_2O) oxides would be common in all plant ash glasses, typically with greater than 1.5 wt% each. Phosphorus pentoxide (P_2O_5) is also associated with plant ashes along with calcium oxide, however as mentioned previously, other sources of lime are known to have been used. On the other hand, mineral sodas such as natron are relatively pure and glasses fluxed with them would show smaller amounts of impurities. Levels of magnesium and potassium oxides would normally be found to fall under 1.5%wt and show little variation (Adlington *et al.* 2020; Ceglia *et al.* 2015; Henderson *et al.* 2004; Henderson 2003; 2013, 23–47; Mirti *et al.* 2008; Phelps 2018; Phelps *et al.* 2016; Rehren & Freestone 2015; Schibille *et al.* 2018).

There have been numerous scientific studies of ancient soda-lime-silica glasses found in the Middle East and in the Late Antique and Early Islamic periods, distinct groups of natron glasses have been identified, each characteristic of specific glass working regions. Adlington *et al.* (2020), Ceglia *et al.* (2015), Freestone (2020), Henderson *et al.* (2004), Phelps *et al.* (2016) and Schibille *et al.* (2019, 2016) all identify natron glasses in the Middle East and even find broad regional differences between Egyptian and Levantine-made products. Egyptian glasses tend to have higher levels of impurities such as iron and titanium oxides than their Levantine counterparts (Phelps *et al.* 2016; Schibille *et al.* 2016). Also, these glasses can be split into different subgroups, perhaps resulting from evolving practices over time or location changes of primary production locations (Schibille *et al.* 2019). Some Egyptian glass groups have been named as such: Egypt 1a, Egypt 1b, Egypt 1c, Egypt 2 (Schibille *et al.* 2019), HIMTa, HIMTb and HLIMT (Ceglia *et al.* 2015; Freestone 1994). First given by Freestone (1994), HIMT is an acronym describing High Iron, Manganese and Titanium levels found in some Egyptian glasses. The acronym HLIMT was first named by Ceglia *et al.* (2015) for glasses with High Lime, Iron, Manganese and Titanium levels to separate this particular type of glass from the HIMT glasses by distinguishing the differing levels of calcium oxide. Levantine glass compositions have also been identified, likely produced at different sites, where Phelps et al. (2016) has labelled them as "Apollonia" and "Bet Eli'ezer" types after both probable production zones. It is also noted that natron glass production showed continuity following the Islamic conquest, and it may not be worth differentiating them as Byzantine or Islamic glasses but simply just natron types. Though Phelps et al. (2016) do show that the shift in primary production to Bet Eli'ezer coincides with the influential reforms of the Umayyad Caliph al-Malik in the late 7th Century CE.

Due to the many factors that affect plant ash glass compositions, it is perhaps expected to see a large amount of variation of impurity levels. Plant ash glass analysed from sites in the Middle East also have characteristic compositions related to their geographic origin. Examples of this include the work of Henderson (2003), Henderson *et al.* (2016, 2009, 2004) Mirti *et al.* (2009, 2008), Phelps (2018) and Schibille *et al.* (2019, 2018). Most notably, findings from Henderson *et al.* (2016) indicate that plant ash glass compositions do show trends relative to their geological origin and that, by using isotopic and trace element analysis, one can relate glass-making specialisation to specific cosmopolitan hubs across the Middle East. We see that glass from eastern locations such as Iran and Iraq tend to have high magnesium oxide levels and low calcium oxide while the more western sites produced glass with lower magnesium oxide levels and higher calcium oxide. It is also noted by Schibille *et al.* (2018, 2016) and Freestone (2015) that recycling can be characterised by small amounts of colourant elements such as lead, cobalt and copper where they are not strong enough to colour the glass but could have resulted from a previously coloured glass entering the mix. Also, contaminants from equipment and fuel ash may result in higher levels of elements like iron in glasses that have been remelted often. Glassmakers were known to have used manganese or antimony (Sb) to decolour glasses so perhaps increased levels of these elements could also mean work was performed by them in an effort to remove the colour introduced by contaminants in the recycling process. By analysing the chemical compositions of glasses found at a particular site, perhaps one could find where they may have travelled from if they indicate signature impurity levels associated with known glassmaking hubs.

3. Site descriptions

3.1. Qasr al-Hayr al-Sharqi, Syria

Qasr al-Hayr al-Sharqi is an early Islamic desert castle and settlement site initially founded in the Umayyad period. Located in the Syrian desert 100km north-east of the settlement of Palmyra and 100km south of al-Raqqa, Qasr al-Hayr al-Sharqi was situated on route between these cities and between lower Mesopotamia and the Syrian Levant as seen in Figure 3 (Grabar 1970).

Figure 3: Map of Syria with red circle indicating the location Qasr al-Hayr al-Sharqi. Image adapted from: http://cherubdistrict.com/database/author/enzo/ Accessed: 07/08/2020

More than what can be just described as a desert castle, it was situated on well-irrigated land with an agricultural community and palatial complex, showing hierarchical structure typical of a new Early Islamic urban settlement (Genequand 2005). A schematic plan of the site can be seen in Figure 4. The first extensive excavation was carried out by Oleg Grabar, analysing the main structures and enclosures of the site (Grabar 1970) and further work followed with the most recent project conducted by a Syrian-Swiss team outlined in Genequand (2008). It is one of the only desert castles founded by an Umayyad caliph, indicated from an inscription on site describing it as a *madīna* or town built by Caliph Hisham in the year 728 CE (Genequand 2005). Though like many other Qasr complexes, its specific purpose is unknown, it was likely to have served as a place of residence for some elite members of Islamic society, perhaps even the Caliph himself (Genequand 2008).

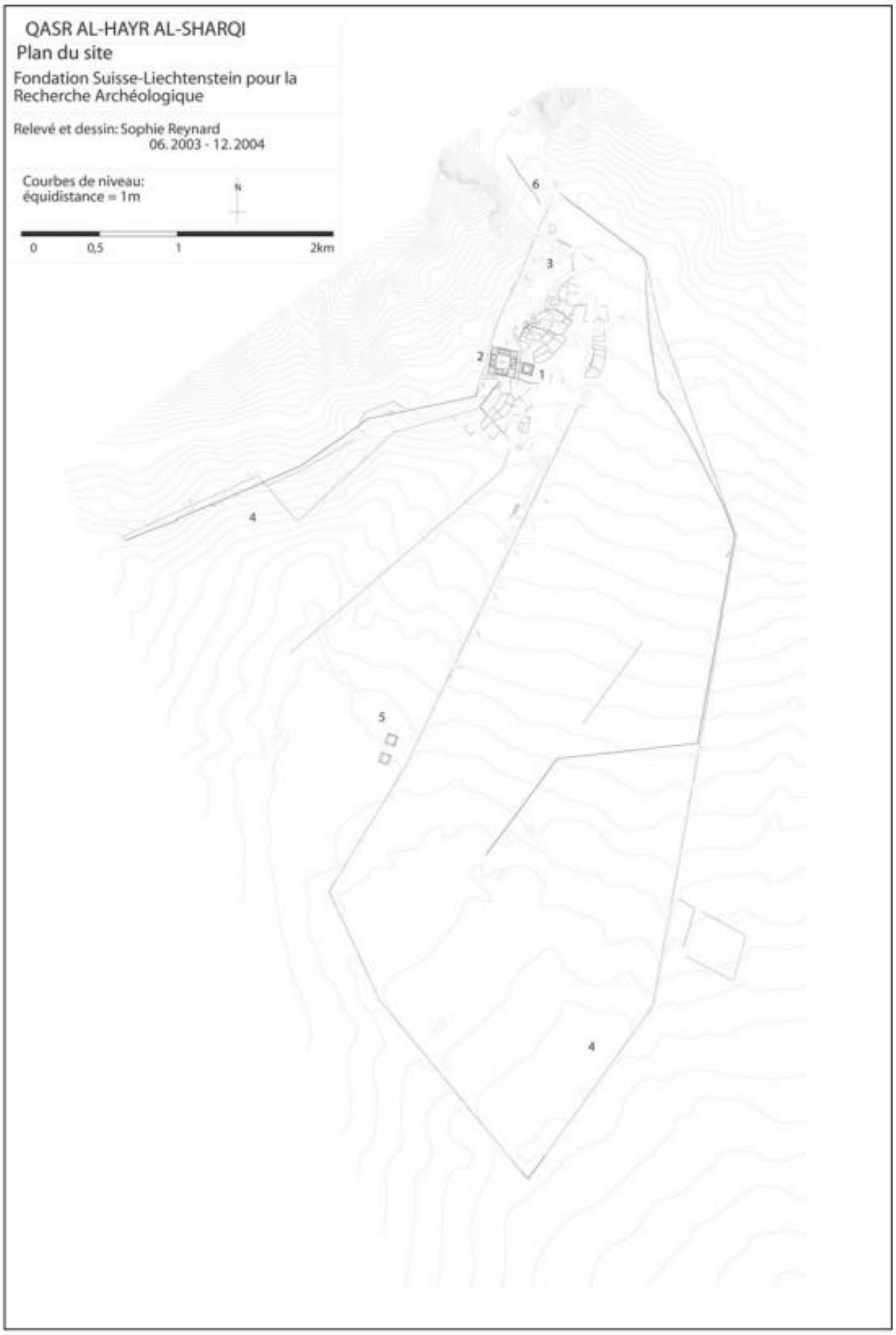

Figure 4: Plan of Qasr al-Hayr al-Sharqi with labels: 1 palace, 2 large enclosure, 3 northern settlement, 4 outer enclosures, 5 southern castles, 6 water mill and aqueduct. Obtained from (Genequand 2008)

Containing what appears to be palace and bath structures and perhaps with private aristocratic apartments for the attendants or administrators of the Caliph, it is clear that it was occupied by the wealthy (Grabar 1970). A great deal of effort was made in order to make the place habitable, where a 30km underground aqueduct or *qanāt* systems brought water from springs in neighbouring settlements (Genequand 2008). Water would have been used in the palace and bath enclosures as well as for irrigation of perhaps a garden or agricultural plot. While the larger structures on the site were most likely used by the presiding elite, mud brick houses in a settlement to the north of the palace was occupied in tandem, containing a watermill and other various domestic appliances such as bread ovens and wine or oil presses (Genequand 2008). Water capture systems such as reservoirs and rain collectors also indicate a permanent occupation in the settlement area, further showing that this was not just a simple retreat for the wealthy (Genequand 2008). Finds of glazed ceramic and glasses indicate the level of prosperity and wealth of those who may not necessarily been of the elite (Genequand 2008). The presence of a storehouse and perhaps stables may also indicate a local economy and the use of domesticated animals for agricultural purposes. It is also speculated that these may have been earlier forms of caravanserai residences given the location of the site relative to local trading routes (Grabar 1970). The material finds on the site at least indicate that Qasr al-Hayr al-Sharqi was connected to Middle Eastern trade networks (Genequand 2008; Grabar 1970).

Since its founding in the 8th century CE, both the stone enclosures and the domestic settlement had continuous occupation, though perhaps the transition from the Umayyad to Abbasid period saw a shift in status of the occupants explained by the gradual abandonment by the elite, until its total abandonment by the end of the 10th century CE (Genequand 2005). Genequand (2008) also hypothesises that the Qasr and surrounding settlement was the result of an Umayyad attempt to found a new urban settlement in the desert, hence the usage of the word *madīna,* with the hopes that its population would expand into a caliphal or aristocratic city able to thrive independently due to its position on local trade networks. Though the difficulty of such an environment meant that this was less possible compared to the more successful attempts such as that at al-Ramla (Genequand, 2008; Luz, 1997; Phelps, 2017, 59). The site saw brief re-occupation in the 12th century CE in the Ayyubid period, with the waterways restored and the previous enclosures repurposed for domestic use. Perhaps as a result of its important location on the Silk Road, Qasr al-Hayr al-Sharqi saw prosperity and expansion similar to that as seen before, but eventually by the 14th century CE it was abandoned for good, perhaps as a result of recent Mongol occupation of Iraq and Iran (Genequand 2005).

Qasr al-Hayr al-Sharqi's location relative to important trading hubs likely resulted in the prosperity of the local population. Indeed, if the site was occupied by settlers, the evidence of traded wares from northern Syria and Samarra indicate the level of connectedness to the surrounding area (Genequand 2008; Grabar 1970). It is perhaps safe to assume that the Qasr was also connected to the glass trade networks of the Middle East (Genequand 2008). As there has not been, as of yet, any evidence of glass working furnaces on the site, the finds may have been imported from nearby centres. At least during the Abbasid period, we know that glass was being made in al-Raqqa just to the north, and so the glass found here may be a direct import from the industry there. Much of the architecture and design of the main enclosures appear to be influenced by Byzantine and Roman design, including even the incorporated use of Roman masonry from Palmyra (Genequand 2008; Grabar 1970). Therefore, glass could have been imported from the Egyptian or Levantine natron glassmakers. Analysis of glass from this site will hopefully allow a glimpse into the local economy and give an idea of how it may have travelled in the Early Islamic Middle East.

3.2. Pella, Jordan

Pella or Fihl is an ancient city located on the Eastern banks of the Jordan Valley, 30km south of the Sea of Galilee and 80km north from the city of Jerusalem as seen in Figures 5 and 6. Its location would have been extremely advantageous strategically and as a result of the historic trade routes going through the area. It was situated on a major road to the region of Jordan from Palestine as seen in Figure 5. It would see almost continuous occupation for millennia preceding the Islamic takeover of the region and it existed as an important urban hub from the Roman to the Islamic periods, containing much activity in both the town and rural areas surrounding it (Smith 1968; Watson & O’Hea 1996).

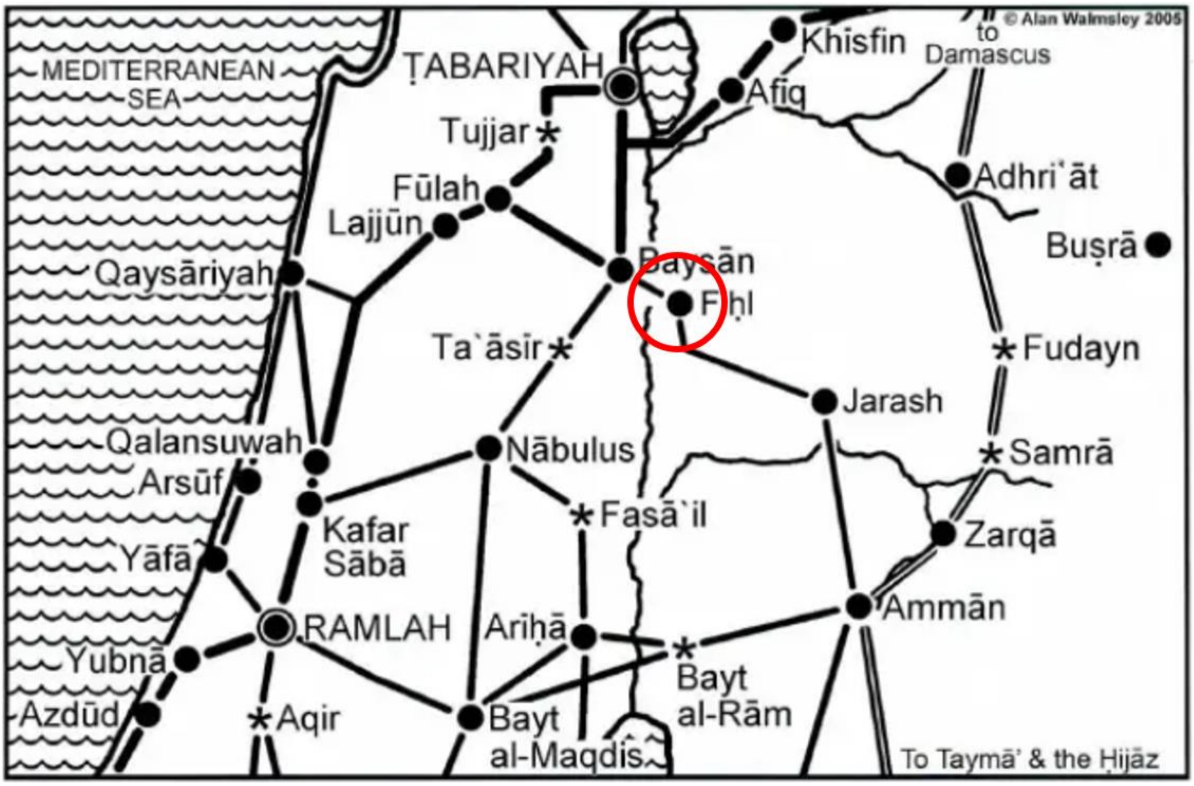

Figure 5: Map of the Jordan valley region with Pella circled in red (Labelled as Fihl). Adapted from (Walmsley 2011)

The first extensive excavation of the site was conducted by a joint Australian-US team generally identifying the main city mound and neighbouring Tell al-Husn separated by Pella’s water-rich valley known as Wadi Jirm al-Maūz. Since 1985 further work under Australian researchers such as Alan Walmsey, Margaret O’Hea, Pamela Watson and Stephen Bourke continued to build a picture of ancient Pella and the people who occupied it (Bourke 2015; Smith 1968; Walmsley 1988; Watson & O’Hea 1996; 1996). Much like the rest of the Levant, Pella saw much continuity after the Islamic conquest. Many of the buildings saw uninterrupted use such as the main Christian churches and cathedral of the area, which even perhaps saw further development. Many of the excavated buildings and complexes are shown on the plan of Pella in Figure 6.

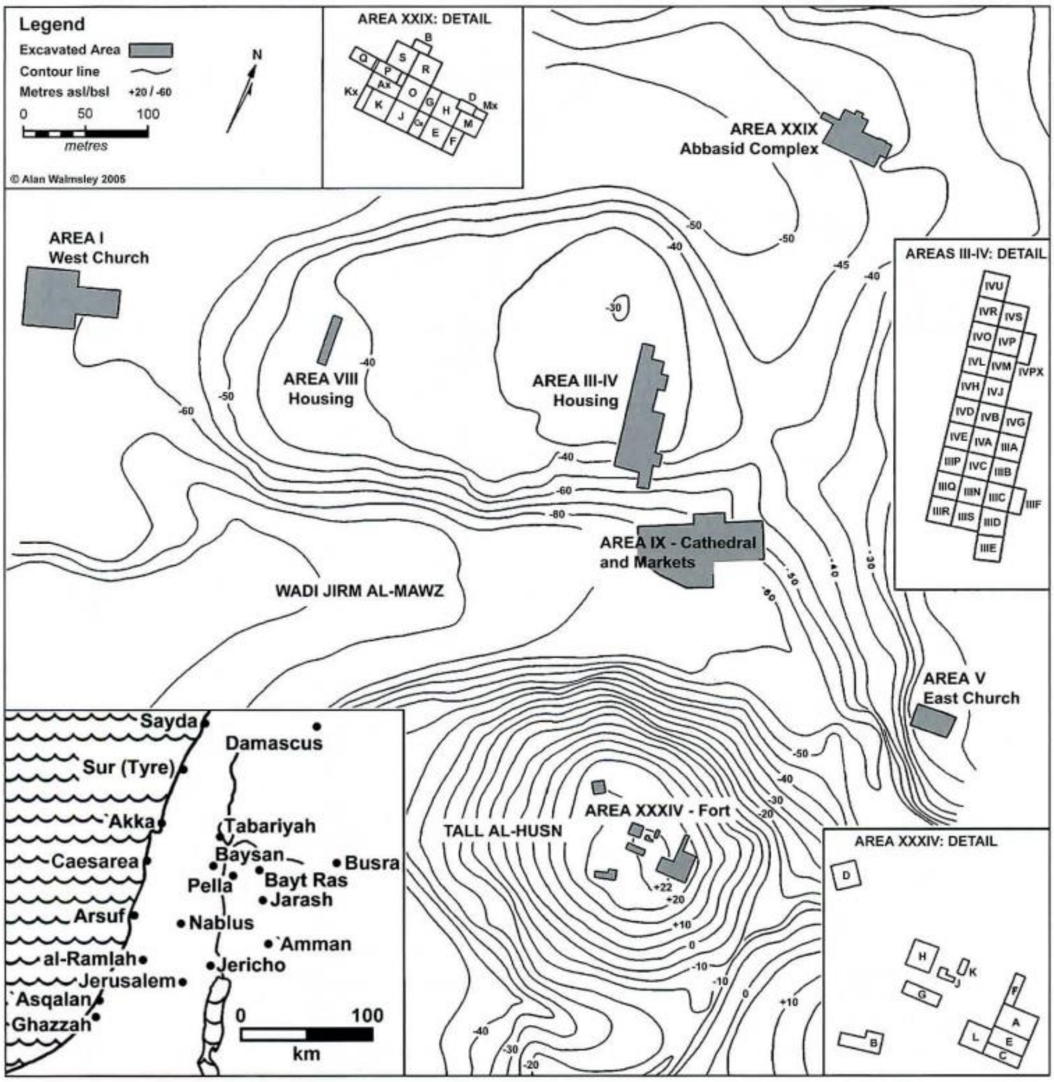

Figure 6: Plan of the archaeological site of Pella. Obtained from (Walmsley 2011)

Even though one of the first major battles between the Byzantines and invading Muslims was named after this location as the Battle of Fihl (635 CE), none of the excavated buildings show signs of destruction – not even the fort on Tell al-Husn. Indeed, perhaps originally built to protect the settlement from foreign invasion, the summit was repurposed into a domestic Muslim quarter (Walmsley 1995). This perhaps indicates the changing sense of security in the region during the Byzantine-Islamic transition where forts were no longer needed to protect from foreign invasion (Watson & O'Hea 1996). The only destruction in the area following the conquest appears to have been caused by an earthquake in 659 CE though the rebuilding and repair process took place in both Islamic and Christian buildings, likely to have been influenced by Byzantine styles and practices. There were also changes in architecture and settlement structure, perhaps as a result of the newly settled Muslims (Walmsley 2011). Pella appears to have been quite prosperous following the conquest too, and there appears to have been an increase in imported metals, glazed wares, glass and gold dinars. Furthermore, some change in the styles of these crafts could be indicative of greater contact with Eastern trade centres, perhaps stimulated by the expanse of the new caliphate (Walmsley 1997a). There is also evidence of a secondary glass workshop in pre-

659 CE Pella, indicating its connection to the local economy and glass trade networks which also appeared to have continued from the Byzantine occupation (O'Hea 2018). In 749 CE a more powerful earthquake struck the region, causing building collapse and trapping daily objects, animals and people under the rubble, giving us a small snapshot of urban life in Early Islamic Pella (Walmsley 2011). Finds of fine silk clothes, Umayyad gold dīnārs and high-status wares from across the Islamic-ruled territories at the time highlight the wealth and strong economy of the region not long after the Islamic expansion (Walmsley 2011). This wealth and evidence of continued occupation despite the damage suggests that there was a level of economic resilience, perhaps highlighting the importance of Pella commercially and administratively (Walmsley 1988; 2011). Seeing evidence of occupation well into the Abbasid period as well as pottery and glass of Abbasid and Fatimid types indicate the relative prosperity and perhaps industry of Pella in the following centuries after the earthquake (Walmsley *et al.* 1993). There is even evidence of a local glass industry in Pella during the Abbasid period, with regionalism different from the mainstream designs produced in Mesopotamia and the Levant at the time (O'Hea 2001; Walmsley 1997b).

While further work is needed in order to uncover the extent of glass working and trade at Pella, it was an important urban hub in Early Islamic Jordan and there was likely movement of glass material in and out of the site (O'Hea 2018). This is reflected in the wide variety of finds at this site extending over a long period of time (O'Hea 2001; Walmsley 1988; 2013, 117–20). In order to supply the secondary glass workshops on site, cullet was likely imported from primary glass working centres in perhaps the Levant and Mesopotamia as well as whole vessels, maybe for the wealthier class of residents in Pella (Walmsley 2008). While not instantly adopted, styles of Syrian and Iranian Abbasid glass clearly had an influence on Jordanian glass production potentially indicating the shift in centralisation spurred by the Abbasids (O'Hea 2001). Pella's position on regionally important roads may have also encouraged large amounts of trade and wealth to be brought to the ancient settlement.

4. Materials and methods

4.1. Glasses from Qasr al-Hayr al-Sharqi

There are eleven glass samples analysed from Qasr al-Hayr al-Sharqi as summarised in Table 1. All are identified as being a soda-lime-silica type. Of this collection, nine are identified as vessel fragments, including beaker and flask rims and bases. One of the pale green glass fragments has been identified as being from a mould-blown vessel. Seven of the glasses have a translucent pale green and blue-green colouration and the remainder have darker green colours and one deep purple or "aubergine" colour. All the glass samples have been dated to the 8th-9th centuries CE by Dr Margaret O'Hea of the University of Adelaide on the basis of discussion with the site director Dr Denis Genequand. All dates and descriptions were provided by Henderson and O'Hea (pers. comms.).

	Colour	**Type**
QHS01	Green	Flask base fragment
QHS02	Pale Green	Indented vessel fragment
QHS03	Pale Green	Mould blown beaker base fragment
QHS04	Pale Green	beaker base fragment
QHS05	Pale Green	Undiagnostic
QHS06	Pale Green	Undiagnostic
QHS07	Blue Green	Rim fragment
QHS08	Pale Green	Base fragment
QHS09	Green	Base fragment
QHS10	Aubergine	Base fragment
QHS11	Dark Green	Flask base fragment

Table 1: Summary of the glasses from Qasr al-Hayr al-Sharqi with description of colour and type provided by Henderson and O'Hea (pers. comms.). Fragments labelled "Undiagnostic" are given to those with an unidentifiable form.

4.2. Glasses from Pella

Forty-nine glass samples excavated at Pella have been analysed as summarised in Table 2. All of these glasses have been identified as being of the soda-lime-silica type. Thirty-nine glasses are of noticeable vessel features such as bases and rims of bowls, goblets, beakers and flasks. Eight glasses can be identified as being part of a blown vessel, five from pincer or tong decorated vessels, two from lustre decorated vessels, one with a trail decoration and one with thread decoration. Of the colours given, 35 glasses are coloured green, blue, blue-green, and yellow-green; six are amber, pale amber, amber-brown and brown; six show deep blue colouration; two are colourless but one of those has a red enamel. The glasses from Pella have been dated from the 9th-10th centuries CE by Dr Margret O'Hea on the basis of discussion with the site director Dr Stephen Bourke. All dates and descriptions were provided by Henderson and O'Hea (pers. comms.).

	Colour	Type		Colour	Type
PEL01	Blue Green	Pincer-decorated fragment	PEL24	Red lustre on Blue Green	Vessel body fragment
PEL02	Pale Green	Goblet base	PEL25	Pale green	Pincer decorated Beaker rim
PEL03	Yellow Green	Mould Blown	PEL26	Green	Bowl Rim
PEL04	Blue Green	Fragment shoulder of bottle	PEL27	Colourless	Thread decorated flask
PEL05	Yellow Green	Beaker rim	PEL28	Pale blue green	lustre decorated rim
PEL06	Blue Green	Pincer decorated	PEL29	Blue Green	Mould Blown
PEL07	Pale Blue	Beaker base	PEL30	Amber Brown	Mould blown fragment
PEL08	Cobalt Blue	Undiagnostic vessel fragment	PEL31	Blue Green	Bowl fragment
PEL09	Blue Green	Nipped beaker base fragment	PEL32	Blue Green	Undiagnostic
PEL10	Blue Green	Base fragment	PEL33	Blue Green	Undiagnostic
PEL11	Blue Green	Rim	PEL34	Blue Green	Undiagnostic blown vessel fragment
PEL12	Blue Green	Beaded rim	PEL35	Green	Bowl rim
PEL13	Amber	Base fragment	PEL36	Pale Amber brown	Undiagnostic blown fragment
PEL14	Cobalt Blue	Undiagnostic vessel fragment	PEL37	Amber	Undiagnostic fragment
PEL15	Blue Green	Base fragment	PEL38	Dark Blue	Lustre deecorated vessel
PEL16	Blue Green	Undiagnostic	PEL39	Yellow Green	Flask
PEL17	Green	Mould blown beaker base	PEL40	Cobalt Blue	Flask neck
PEL18	Dark Blue	Outfolded rim	PEL41	Red enamel - colourless	Vessel
PEL19	Blue Green	Bowl rim	PEL43	Pale Green	Undiagnostic
PEL20	Pale Green	Nipped beaker	PEL44	Pale Green	Thin blown
PEL21	Pale Green	Bowl rim	PEL45	Yellow Green	Pincer decorated beaker
PEL22	Brown	Tong decorated	PEL46	Pale Green	Bowl Rim
PEL23B	Pale Green	Vessel fragment	PEL47	Cobalt Blue	Undiagnostic
PEL23A	Amber	Trail on vessel fragment	PEL48	Blue Green	Goblet
			PEL49	Blue Green	Undiagnostic blown vessel fragment

Table 2: Summary of the glasses from Pella with description of colour and type provided by Henderson and O'Hea (pers. comms.). Fragments labelled "Undiagnostic" are given to those with an unidentifiable form.

4.3. Sample preparation

Glass samples were prepared for electron probe microanalysis (EPMA) by having small fragments of 1-2mm mounted in epoxy resin and polished flat using diamond paste in order to create a homogenous surface and prevent shadow effects as described in Leng (2010). Further detailed in Henderson (1988), a series of grades of diamond paste would be used down to 0.25µm and then a layer of carbon was applied after the surface is cleaned in order to prevent localised static charging which could cause distorted images. Carbon is particularly useful due to its transparency and conductivity of electrons and is applied in a vacuum to prevent any contamination (Limandri *et al.* 2010).

The mounted glasses were scanned in the in the Department of Archaeology at the UK campus of the University of Nottingham when there was an EPMA machine there at the time. The machine used for the analysis was a JEOL JXA-8200 electron microprobe, equipped with four wavelength-dispersive X-ray spectrometers, an energy-dispersive X-ray spectrometer and detectors for both backscattered and secondary electrons. A 20kV voltage was then applied to accelerate the electrons forming an incident beam current of 40nA onto the samples. A 50µm defocused electron beam was used in order to minimise the effect of volatile elements migrating away from the point of impact. The beam was applied to the same spot a minimal number of times in order to prevent latent volatility. The results provided in this paper were produced under the supervision of Dr Julian Henderson of the University of Nottingham by Dr Edward Faber as access to the necessary equipment was prevented to the author due to the restrictions imposed as a result of the COVID-19 pandemic. All data analysis and discussion of these findings are, however, of the author's own work.

4.4. Overview of Electron Microprobe Analysis

Electron Probe Microanalysis or EPMA is one of the most useful means of analysing silicates, able to quantify the presence of major and minor oxide components over a wide range of elements in glasses. First developed by Castaing (1951), its application has been seen in a wide range of fields including material sciences, geology and archaeology. The equipment functions by analysing how a material sample interacts with a beam of electrons accelerated by an electron gun. Using a cathode ray, acceleration voltage would be set by the user, normally adjusted depending on the nature of the material set to be scanned. Different atoms would interact with electrons to different degrees. Heavier elements would deflect the oncoming electrons thus resulting in little penetration of the beam and perhaps giving incomplete results, although, too strong of an acceleration would result in greater lateral movement of electrons within the material and therefore a lower resolution of useable data (Llovet *et al.* 2020). Using an electromagnetic lens system, the beam is then focused onto the target material and a number of detectable phenomena are produced as shown in Figure 7. A typical EPMA machine would have a secondary electron detector, backscattered electron detector, optical microscope, wavelength-dispersive spectrometer (WDS) and an energy-dispersive spectrometer (EDS) as is shown in Figure 8. Secondary electrons would be freed from their respective atoms through the scattering of the beam electrons, relatively low in energy (< 50eV), mostly emitted from the immediate surface levels of the material. The detection of these can aid in determining the topographical features of the material, though perhaps not useful when scanning a sufficiently homogenous surface (Llovet *et al.* 2020). Backscattered electrons are the result of beam electrons being reflected by the atomic repulsion and the strength of this signal is normally indicative of the average atomic mass of the beam target in the material, though perhaps not very useful in finding the components of the material. The optical microscope would mainly be used to adjust material on the mount, perhaps for aiming purposes as its resolution would be too low for any useful magnification. Though some information can be gained from emitted optical light, this is mainly focused around structural analysis of material in EPMA, which is less useful for amorphous solids such as glass (Llovet *et al.* 2020; Remond *et al.* 2000).

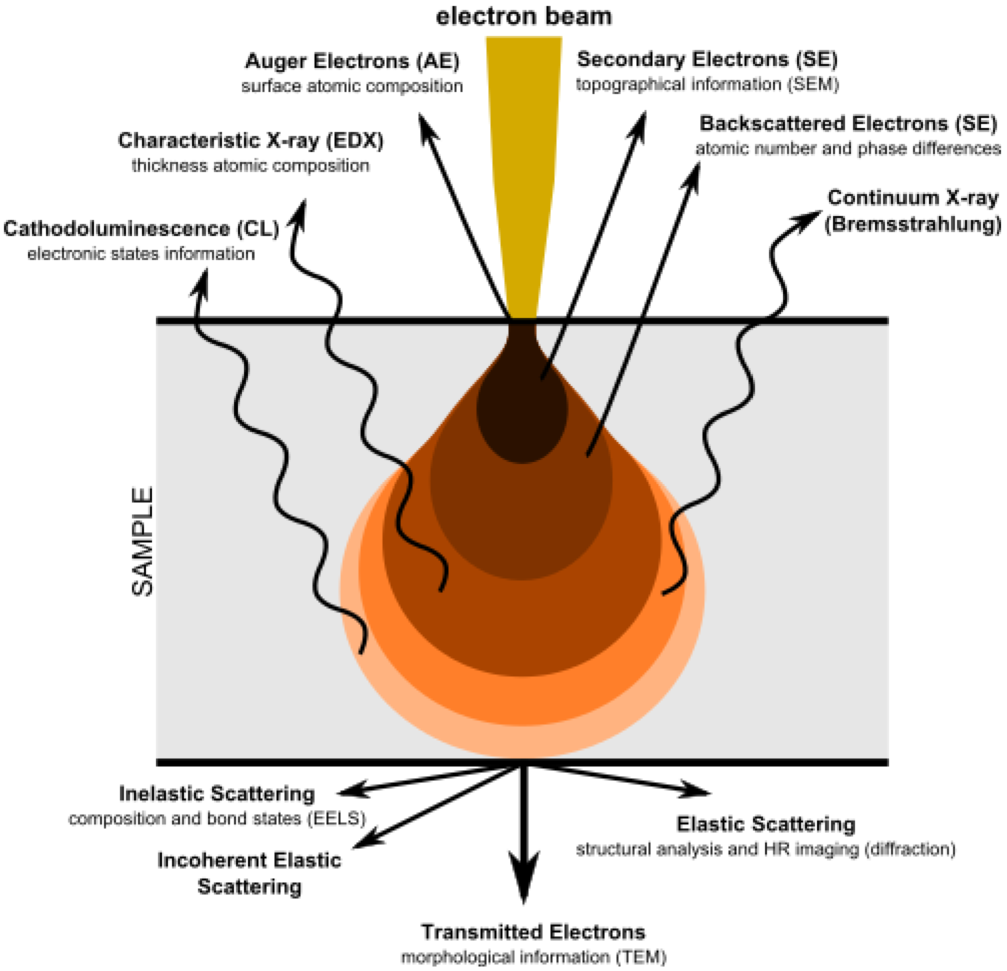

Figure 7: Diagram of the interaction volume of an electron beam and focussed on a solid sample, showing the various detectable phenomena and where they originate from. Obtained from https://users.aber.ac.uk/ruw/teach/334/sem.php Accessed: 08/10/2020

The two spectrometer choices in EPMA are either wavelength or energy dispersive spectroscopy. Electrons approaching atoms in the material may also experience a deceleration from the electrostatic field of the orbiting electrons. The conservation of energy would dictate then that electromagnetic energy must be released as this deceleration occurs. This comes in the form of Bremsstrahlung radiation, forming a continuum of radiation from 0eV to the energy of the beam electrons. As these electrons typically are accelerated to the KeV range, most of the photons in this radiation are X-rays (Semaan & Quarles 2001). Furthermore, the energy of the beam electrons is enough to displace electrons in the inner shells of the atoms they encounter, thus leaving an imbalance of charge in those shells. The resultant readjustment of electrons in the atom following this ejection of an inner electron results in outer shell electrons releasing energy in order to fill the gap. Due to the quantum nature of electron energies, only specific discrete amounts of energy can be released in the process. These energies are unique to the element of the atom, and so one can record the energy profiles released from such a process and determine what elements are present (Llovet *et al.* 2020). The energy required to remove these inner-shell electrons typically is in the keV range, therefore when the space they occupied is filled by the outer electrons, the electromagnetic energy released in this process is also in the same range and thus producing X-Rays. Wavelength dispersive spectrometers then take the X-Rays emitted in this process and focus it through a crystal set-up dictated by Bragg's law:

$$n\lambda = 2d\sin\theta, \tag{1}$$

Where λ is the wavelength of the X-ray, n is the integer diffraction order of the diffraction, d is atomic spacing of the crystal in use and θ is the angle of incidence of the X-ray onto the crystal. By determining the type of crystal used, thus atomic spacing d, and the angle at which the X-rays are beamed onto it, one can then determine the wavelength of the X-ray produced. In EPMA the crystal would be mechanically moved so the focus of the diffracted beam sits on what is called a Rowland diffraction circle, specifically to a position where $n = 1$, thus finding the exact wavelength (Llovet *et al.* 2020; Reed 2005). In order to cover a wide wavelength range so that many elements can be characterised, many different kinds of crystals would be used in order to vary the atomic spacing value. Some of the common crystal types are: lithium fluoride (LiF), pentaerythritol (PET) and thallium acid phthalate (TAP) (Llovet *et al.* 2020). After scanning through the X-ray range, one would find many wavelength peaks and therefore be able to compare to known element profiles and determine which are present in the scanned material. Moreover, by comparing the intensity of these peaks to standard materials of known composition, one could find exactly how much of each element is present. For example, when scanning ancient soda-lime-silica glasses, the standards Corning A and B are often used due to their similarities to natron and plant ash glass compositions (Adlington 2017).

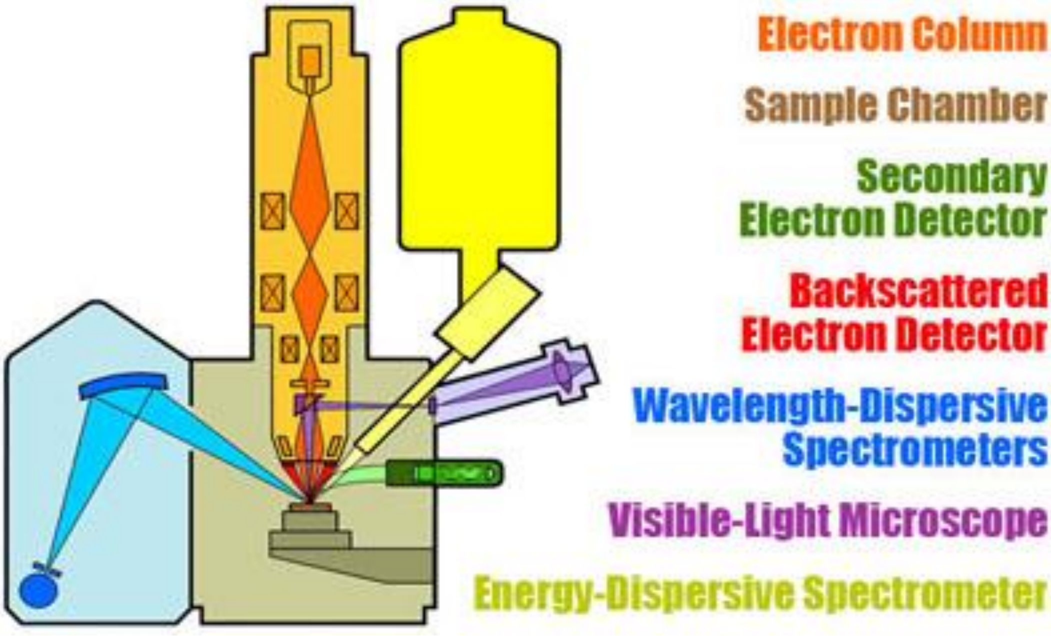

Figure 8: Simplified diagram of a typical EPMA setup. Obtained from: https://serc.carleton.edu/research_education/geochemsheets/techniques/EPMA.html Accessed: 09/10/2020

Conversely, an energy dispersion spectrometer would consist of a detector measuring the energy of the X-rays emitted from the material. Scanning for energies over the X-ray range, it would find peaks corresponding to the discrete energy emissions from the collision process described previously. Comparing these peaks to the known energy profiles of specific elements, one can work out the composition of the materials being scanned. As well as this, the intensity of these peaks would be compared to the result from a known standard, thus allowing one to find the relative amounts of these elements (Llovet *et al.* 2020). Although each element has a distinct energy emission profile, some overlap can be seen of these energy peaks where the energy for one orbital transition of one element may be very similar to another from a different element. While EDS tends to be a quicker and more widely available process, WDS is a more precise method of spectrometry and is able to distinguish the overlap more effectively (Llovet *et al.* 2020; Wilson 2017).

With the analysis of glass, often EDS is used for major elemental oxides as the greater error would be less significant, while WDS and its greater precision was more useful for minor oxide components. The same procedure would have been applied to the analysis of the samples mentioned above. Using apparatus similar to that described in Figure 8, both would have been calibrated against the Corning A and B standards periodically to check the precision and accuracy of the analyses and then corrected using a ZAF program. 25 elements were determined in total: sodium (Na), titanium (Ti), silicon (Si), tin (Sn), aluminium (Al), zinc (Zn), sulphur (S), nickel (Ni), arsenic (As), copper (Cu), chlorine (Cl), cobalt (Co), magnesium (Mg), potassium (K), antinomy (Sb), iron (Fe), barium (Ba), manganese (Mn), calcium (Ca), zircon (Zr), lead (Pb), chromium (Cr), phosphorus (P), vanadium (V) and strontium (Sr). These were measured and recorded in terms of the % weight of their oxides. The data was processed in Microsoft Excel and each sample's results were summed to check if they totalled to 100%. Small variation in the total % weight is expected in all samples due to various reasons such as volatile ion displacement, unaccounted for elements and random error in the machinery and scanning instruments (Henderson 1988). Due to this, all glasses with a total % weight of 97% and above were used in the analysis while those that had less than 97% were discarded. Comparative biplots of two sets of oxides and ratios were drawn in order to determine compositional groupings of the data.

5. Results

5.1. Results of Qasr al-Hayr al-Sharqi analyses

5.1.1. EPMA results of the Qasr al-Hayr al-Sharqi glasses

When looking at the K_2O and MgO components of the glass from Qasr al-Hayr al-Sharqi one can see two distinct groups, one with values bellow 1.5 wt% in both oxides and the other with values above 3.5 wt% of MgO and 1.5 wt% of K_2O as seen in Figure 9. As mentioned previously, these compositions are indicative of the raw materials used to provide the soda source. It is likely that the group with the low K_2O and MgO constituents were made using a mineral soda source and the other with plant ash and typically they are called natron and plant ash glass respectively. While most of the natron glasses are in a group with minimal variation, QHS05 and QHS07 both deviate from the rest with slightly elevated oxide levels, and as suggested by Jackson and Paynter (2016), this may be a result of some recycling. The plant ash glasses show much wider variation which perhaps is a result of the variability of plant ash compositions as shown in Barkoudah & Henderson (2006), or even that the raw materials used to make them are from very different geographical locations. Of the Qasr al-Hayr al-Sharqi group, seven are identified as natron glasses and four are plant ash glasses.

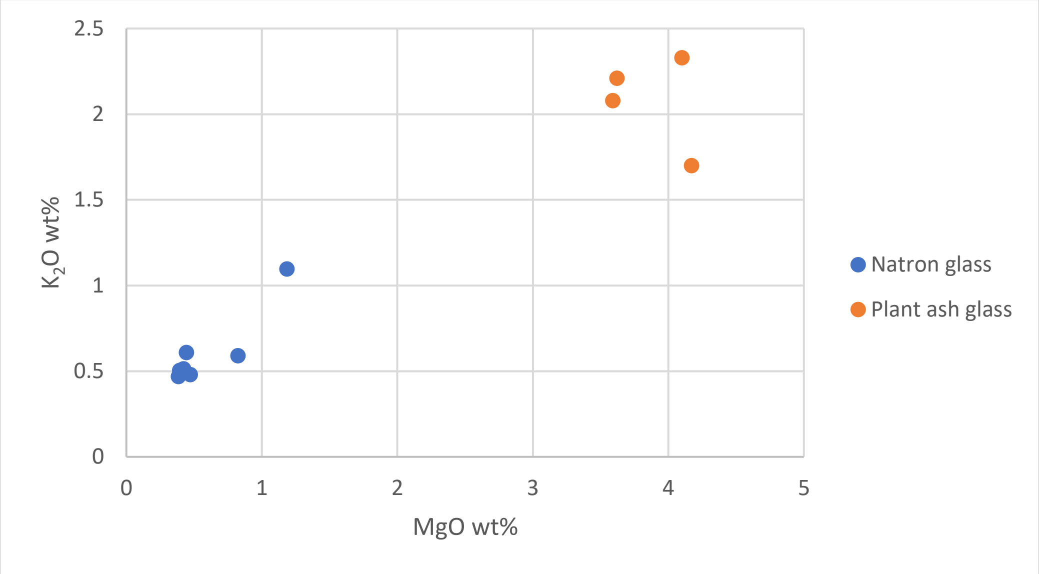

Figure 9: Biplot of K_2O against MgO wt% showing a distinction between natron and plant ash glasses from Qasr al-Hayr al-Sharqi

Both groups can also be differentiated by their silica content. As seen in Tables 3 and 4 below Natron glass has an average silica content of 70.3 wt% which is roughly 10 wt% greater than that of the plant ash glasses. Though conversely, other oxides associated with the silica source such as FeO, TiO_2 and Al_2O_3 show similar levels in both types. In Figure 10 however, the ratio of iron impurities relative to silica is greater in the plant ashes (with the exception of QHS05 and QHS07), perhaps as a result of a more impure silica source being used. Also, in the plant ash glasses, the average CaO content (9.1 wt%) appears to be greater but more variable than that of natron glasses (6.0 wt%), perhaps related to the nature of CaO content in different plant ashes. The ratio of Ca to Al_2O_3 in Figure 10 show perhaps whether the lime component came from an additional ingredient such as feldspar or a bone/shell source (Freestone *et al.* 2000). Though the variation in natron glass lime is less than that of plant ash glasses as seen in the standard deviations in Tables 3 and 4 and Figure 10, the natron glass QHS08 has a comparable CaO/Al_2O_3 ratio to plant ash glasses. It is also worth noting that as found by Barkoudah & Henderson (2006) that phosphorus content is likely correlated with potassium and the plant ash glasses do in fact, on average, demonstrate higher P_2O_5 levels (0.26 wt%) than that of the natron type (0.06 wt%).

Plant ash	Na2O	TiO2	SiO2	SnO2	Al2O3	ZnO	SO3	NiO	As2O5	CuO	Cl	CoO	MgO	K2O	Sb2O5	FeO	BaO	MnO	CaO	ZrO2	PbO	Cr2O3	P2O5	V2O3	SrO
QHS01	14.21	0.203	59.6		3.86	0.034	0.137	0.001	0.044		0.734		4.17	1.7	0.114	1.113	0.025	0.031	10.94				0.331		
QHS09	14.94	0.167	60.83		3.25	0.033	0.224	0.001	0.031	0.051	0.619	0.001	3.59	2.08	0.104	1.45	0.042	0.585	9.02	0.015	0.011		0.242		
QHS10	14.82	0.128	62.54		2.66	0.004	0.171		0.072	0.011	0.702		3.62	2.21	0.149	0.759	0.029	2.32	6.94	0.004	0.049		0.22	0.015	
QHS11	14.85	0.199	59.29		3.63	0.016	0.279	0.006	0.047	0.037	0.44	0.006	4.1	2.33	0.174	1.67	0.023	0.553	9.69	0.002	0.004		0.265		
Average	14.683	0.145	70.253		3.131	0.001	0.106	0.003	0.001	0.012	0.762	0.000	0.588	0.609	0.033	0.616	0.069	0.041	6.011	0.007	0.048		0.064	0.007	
Std.	1.318	0.098	1.948		0.295	0.003	0.045	0.004	0.002	0.015	0.088	0.001	0.281	0.205	0.018	0.334	0.041	0.056	0.845	0.014	0.057		0.029	0.006	

Table 3: Results of chemical analyses of Plant ash glasses from Qasr al-Hayr al-Sharqi in oxide weight %. Blank spaces represent undetected oxides. Table includes the averages and standard deviations of this group.

Natron	Na2O	TiO2	SiO2	SnO2	Al2O3	ZnO	SO3	NiO	As2O5	CuO	Cl	CoO	MgO	K2O	Sb2O5	FeO	BaO	MnO	CaO	ZrO2	PbO	Cr2O3	P2O5	V2O3	SrO
QHS02	13.87	0.075	72.18		2.99		0.167				0.784		0.471	0.481	0.012	0.422	0.085	0.007	6.27	0	0.03		0.048	0.018	
QHS03	15	0.079	70.98		2.91		0.156	0.009		0.013	0.839		0.393	0.504	0.037	0.367	0.11	0.016	6.09				0.045	0.006	
QHS04	13.87	0.079	70.49		3.18		0.053	0.008		0.018	0.682	0.003	0.421	0.515	0.014	0.423	0.122	0.031	5.86		0.162		0.038	0.009	
QHS05	17.39	0.258	66.8		3.54		0.133	0.006		0.005	0.901		0.822	0.59	0.034	0.939	0.089	0.029	4.58				0.093	0.008	
QHS06	12.98	0.099	72.66		3.2		0.115				0.62		0.443	0.609	0.068	0.471	0.033	0.02	6.36	0.039	0.006		0.042		
QHS07	15.32	0.334	68.14		3.47	0.009	0.052		0.007	0.046	0.723		1.183	1.097	0.045	1.3		0.177	5.38	0.013	0.102		0.12	0.011	
QHS08	14.35	0.092	70.52		2.63		0.065			0	0.786		0.383	0.47	0.019	0.391	0.042	0.01	7.54		0.033		0.063		
Average	14.705	0.174	60.565		3.350	0.022	0.203	0.003	0.049	0.025	0.624	0.002	3.870	2.080	0.135	1.248	0.030	0.872	9.148	0.005	0.016		0.265	0.004	
Std.	0.289	0.030	1.277		0.454	0.012	0.054	0.002	0.015	0.020	0.114	0.002	0.266	0.237	0.028	0.345	0.007	0.864	1.449	0.006	0.019		0.042	0.006	

Table 4: Results of chemical analyses of natron glasses from Qasr al-Hayr al-Sharqi in oxide weight %. Blank spaces represent undetected oxides. Table includes the averages and standard deviations of this group.

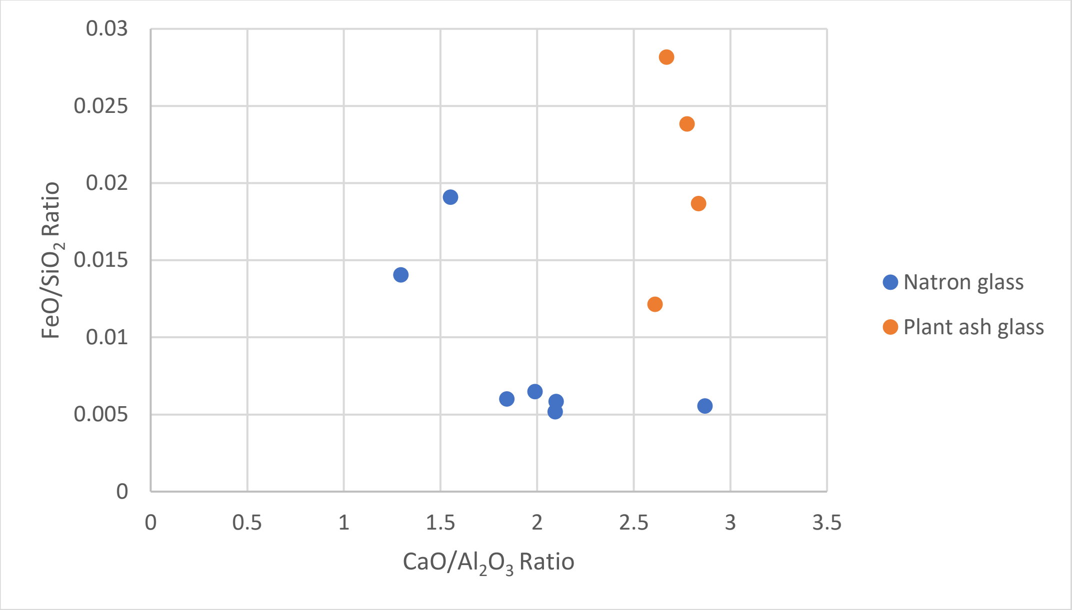

Figure 10: Biplot of the ratios of FeO/SiO2 against CaO/Al2O3 showing distinction between natron and plant ash glasses of Qasr al-Hayr al-Sharqi

In Figure 11 we can also see some greater variation in the natron glasses when comparing relative levels of TiO_2 and Al_2O_3. QHS05 and QHS07 continue to deviate from the rest of the natron glasses, perhaps further suggesting that they were made using different silica sources. There is little deviation in this value for the plant ash glasses however, suggesting a similar use of silica source. Though QHS01 does show a significantly different P_2O_5 level to the other plant ash glasses, which may indicate a different plant ash composition, these differences could have arisen from other variable factors when it comes to plant ash, as the other plant ash glasses seem to be more tightly grouped and perhaps are more closely related in relation to raw material usage.

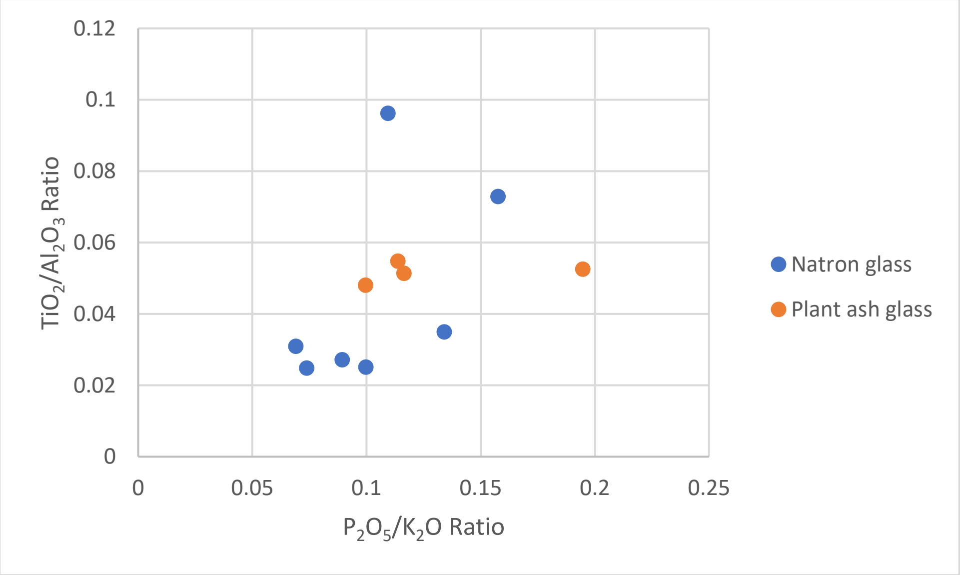

Figure 11: Biplot of the ratios of TiO2/Al2O3 against P2O5/K2O showing separation of Qasr al-Hayr al-Sharqi natron and plant ash glass types and the glasses within

5.1.2. Colours of the Qasr al-Hayr al-Sharqi glasses

All the natron glasses - bar one - have the same colouration of pale green. These glasses do not have any obvious colourants added to them, so it is likely that the pale green colouration has arisen "naturally" through the small amounts of impurities brought by the sand. Depending on its oxidation state, the small amounts of iron would introduce this colour. QHS07 is a slightly darker blue-green colour and this may arise from the higher concentrations of FeO (1.3 wt%) present in the glass. It is also worth noting that there is a slightly higher amount of MnO (0.18 wt%) in this particular glass, which, depending on the oxidation state, may have affected the colour too. Though MnO has typically been used as a decolourant in natron glasses so perhaps it was introduced in an effort to minimise the effect of the higher FeO levels present in the glass. It is also worth noting that the threshold for natural levels of MnO is 0.03 wt%, which is above most of the natron glasses, therefore it is assumed that no attempt at decolouration was applied to them except QHS07 which shows a much higher level. Though the glass did result in a green colour, this may have been the desired effect from just a small amount that had been added (Adlington *et al.* 2020).

Of the plant ash glasses, QHS01, QHS09 and QHS11 are coloured green. This may have arisen from the higher levels of silica contaminants in the glass; relative to the silica levels these glasses have a greater ratio of TiO_2, P_2O_5 and FeO than the natron glasses, so perhaps a stronger colour is expected. Though higher than the natron glasses, the MnO in these three samples may also contribute an effect to their colours (Adlington *et al.* 2020). Perhaps used to decolourise the effects of the previously mentioned impurities, it did not remove the colour entirely but may have prevented them from displaying "typical" plant ash glass colours such as amber and brown. The glass sample QHS10 is coloured deep aubergine which may have been a result of the high levels of MnO (2.32 wt%), known to produce a deep purple colour when melted in the right oxidation conditions (Henderson 2013, 67).

Plant ash glasses also on average have higher levels of Sb_2O_5 (0.13 wt%) than the natron glasses (0.03 wt%). Though used commonly in the early Roman glasses to decolourise them, it was being replaced by manganese rich minerals for this purpose, as is seen in the natron glasses. The levels of Sb_2O_5 in the plant ash is not significant enough to be used for this purpose or opacification however, and, as well as this, the low levels of lead in these glasses show it was not added as a bi-product of lead minerals for colouration. This could have been a result of repeated remixing of previously antimony-rich glasses, though since it was typically natron glasses that would have had antimony oxide, perhaps some inter-mixing between plant ash glasses could have occurred to produce compositions seen here (Freestone & Stapleton 2015).

5.2. Results of Pella analyses

5.2.1. EPMA results of the Pella glasses

The K_2O and MgO weight compositions of glass from Pella have been plotted in Figure 12. Glasses with a MgO component greater than 1.5 wt% have been designated as plant ash glass and those below this threshold are named natron glasses with the exception of three. The glasses PEL45, PEL46 and PEL47 show abnormally low MgO and high K_2O compositions for both plant ash and natron glasses. These oxide compositions are reminiscent of North European woodash glass, though typically even these have a greater MgO level. These three glasses have been grouped as outliers. Between the natron and plant ash glasses, a general positive correlation of these oxide wt% is noted beyond the tighter main natron glass group, which is likely a result from the general correlation between the two in plant ashes as well as potential recycling of these glasses (Barkoudah & Henderson 2006). As seen in the standard deviations in Table 5 below, as well as the spread in Figure 12, there is a greater spread of compositions of natron glass type than the Qasr al-Hayr al-Sharqi glasses, though this may just be a result of the larger sample size.

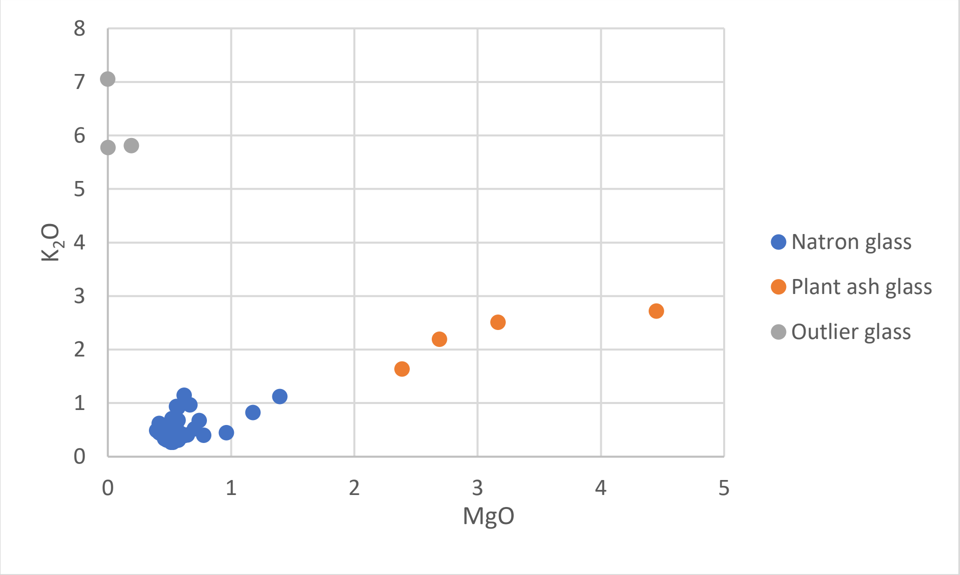

Figure 12: Biplot of K_2O against MgO wt% showing a distinction between natron plant ash and outlier glasses from Pella

As is evident in Figures 13 and 14 and Tables 5 and 6 below the Pella plant ash and natron glasses show more overlap in the minor element oxides. This does make it more difficult, however, to compare the plant ash and natron glasses to each other. In Figure 13 for example, there does not seem to be much difference in the lime source between plant ash glasses and many natron glasses. At least relative to alumina, the lime levels appear to be similar for many of the plant ash and natron glasses. Though in this figure, there appears to be subgroups of natron glasses. Natron glasses with low FeO/SiO_2 and CaO/Al_2O_3 ratios seem to form one of these subgroups, distinguished by the low level of iron impurities in the silica source and minimal amount of calcium introduced from feldspars. This could indicate that this subgroup was produced using a relatively pure silica source, or that it may not have seen much recycling since its fusion. Plant ash glasses show a greater amount of iron impurities compared to this subgroup and therefore may be a result of a less pure silica source. However, many natron glasses also have similar levels of FeO relative to silica and so may have been produced using a similarly impure silica source as the plant ash glasses. The natron glass PEL43 has a relatively high level of Al_2O_3 (4.19 wt%) and low level of CaO (2.64 wt%), compared to the averages of this group (2.72 wt% and 8.49 wt% respectively). Though both of these oxides can act as stabilisers, it may indicate that they were produced using alternative raw materials to typical natron glass types. Also, the plant ash glass PEL03 has a low Al_2O_3 content (0.81 wt%) compared to the group average of 1.79 wt% but a high CaO level (11.17 wt%) relative to the average of 8.25 wt%. This may indicate the use of a pure silica source and the addition of calcium-rich shell or bone fragments instead of a feldspar for a lime source (Henderson 2013, 65).

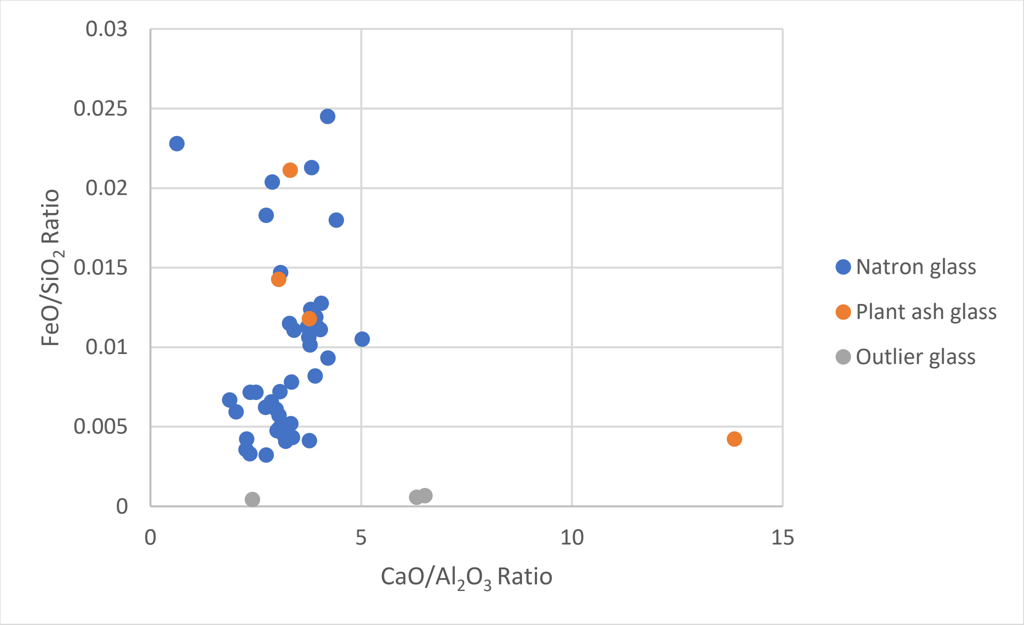

Figure 13: Biplot of the ratios of FeO/SiO_2 against CaO/Al_2O_3 showing distinction between natron, plant ash and outlier glasses of Pella

From Figure 14 we can similarly see a subgroup of natron glasses with low levels of the silica impurity TiO_2, perhaps further indicating that a purer source of silica was selected for the fusion of these glasses. This subgroup also has a relatively low level of P_2O_5 which also reflects on the purity of the soda source. On average the natron glasses have a lower P_2O_5 level (0.11 wt%) than the plant ash glasses (0.28 wt%) which is as expected, though two of the plant ash glasses have phosphorus content comparable to that of the natron glasses. This could potentially indicate that the two plant glasses (PEL12 and PEL44) may not have actually used plant ash as a soda source. As seen in Jackson & Paynter (2016), the higher levels of MgO and K_2O may be just a result of repeated recycling of natron glasses. It is also evident from Figure 14 that beyond the aforementioned subgroup, natron glasses have a wider spread of P_2O_5 perhaps showing that these were as a result of recycling too. Indeed, the higher amounts of titanium oxide and iron oxide could be a result of recycling.

Natron	Na2O	TiO2	SiO2	SnO2	Al2O3	ZnO	SO3	NiO	As2O5	CuO	Cl	CoO	MgO	K2O	Sb2O5	FeO	BaO	MnO	CaO	ZrO2	PbO	Cr2O3	P2O5	V2O3	SrO
PEL01	14.609	0.242	69.148	0.025	2.374	0.057	0.059	0.096			1.228	0.043	0.571	0.312		0.776	0.038	0.019	9.44		0.014	0.01	0.104		
PEL02	15.453	0.281	68.887		2.27		0.116	0.008	0.006	0.024	1.138	0.099	0.48	0.309		0.642	0.031	0.051	9.565				0.094		
PEL04	13.604	0.05	70.899	0.042	2.995	0.038	0.035	0.064	0.002	0.056	0.791		0.397	0.491		0.252	0.055	0.004	6.793		0.027	0.007	0.051		
PEL05	16.054	0.081	69.401	0.017	2.674	0.214	0.115			0.027	0.92	0.092	0.556	0.937		0.342	0.049	0.022	8.353		0.077	0.029	0.115		
PEL06	15.934	0.209	67.07		2.501	0.394	0.153			0.07	1.071	0.106	0.488	0.356	0.039	0.742		0.054	8.514		0.021		0.124		
PEL07	15.619	0.236	66.681	0.002	3.281		0.232	0.064	0.006	0.038	1.012	0.057	0.778	0.397		1.219	0.002	0.194	9.011		0.081		0.16		
PEL08	15.48	0.244	66.935		2.212	0.338	0.098	0.04	0.016	0.133	0.948		0.577	0.451		1.64	0.084	0.109	9.298		0.169		0.235		
PEL09	15.586	0.205	67.931	0.023	2.604	0.076	0.106	0.072	0.022	0.059	0.796	0.12	0.579	0.433	0.023	0.721		0.061	9.789		0.129		0.108		
PEL10	14.486	0.262	67.101	0.043	2.085		0.18	0.048	0.025	0.005	1.215		0.461	0.336		0.704	0.008	0.772	10.478		0.033		0.176		
PEL11	14.18	0.157	65.443		2.383	0.024	0.041		0.03	0.029	0.711	0.042	1.394	1.124	0.101	0.81		0.404	9.058		0.172		0.233		
PEL13	16.141	0.107	69.007	0.026	2.788	0.029	0.124		0.068	0.06	0.809		0.559	0.638	0.117	0.339	0.083	0.068	8.514		0.073	0.025	0.142		
PEL14	14.8	0.225	67.517		2.21	0.266	0.072	0.008	0.009	0.072	0.98	0.099	0.598	0.422		1.214	0.022	0.067	9.738		0.087	0.034	0.233		
PEL15	13.187	0.136	67.972	0.039	2.897	0.185	0.064	0.04	0.005	0.097	0.728		0.566	0.914		0.49	0.021	0.038	8.906		0.022	0.03	0.199		
PEL16	13.861	0.23	68.104	0.026	2.328		0.1	0.008	0.046		1.11	0.028	0.49	0.311		0.767			8.667				0.062		
PEL17	14.471	0.262	67.434		2.459		0.092		0.01		0.865		1.177	0.823		0.684	0.017	0.174	9.316		0.064	0.019	0.135		
PEL19	14.932	0.295	69.125		2.339		0.035	0.016			1.09		0.512	0.267		0.768		0	9.419		0	0.047	0.061		
PEL20	14.318	0.078	71.396		3.288	0.014	0.06	0.151			0.95		0.489	0.557	0.015	0.302	0.028	0.046	7.51		0.022	0.042	0.106		
PEL21	15.188	0.251	68.298	0.022	2.307		0.101	0.032	0.027	0.065	1.088	0.014	0.619	0.395		0.871	0.042	0.176	9.342		0.065	0.005	0.185		
PEL22	13.863	0.085	73.392		3.202		0.042	0.04	0.016		0.881		0.533	0.479		0.435	0.094	0.075	6.499	0.095	0.015		0.091		
PEL23B	14.157	0.066	72.685	0.023	2.912		0.067	0.008	0.024		1.014	0.085	0.418	0.621		0.24		0.024	6.859		0.017	0.026	0.047		
PEL23A	13.747	0.054	71.216	0.017	2.832		0.074			0.047	0.858	0.014	0.435	0.549		0.229	0.042	0.011	7.774	0.085	0.006		0.107		
PEL24	13.887	0.059	69.464		2.686		0.118				0.852	0.078	0.429	0.428		0.284	0.009	0.049	8.625		0.039		0.049		
PEL25	17.4	0.09	65.21		2.2	0.034	0.104	0.003			0.837	0.002	0.666	0.967	0.461	0.534	0.021	0.622	8.6	0.004			0.14	0.013	
PEL26	14.203	0.112	68.397		2.985		0.012	0.032		0.051	0.818	0.014	0.619	1.144		0.448	0.001		8.557	0.033	0.178	0.041	0.295		
PEL27	14.957	0.039	69.223	0.043	2.814		0.09		0.007	0.05	0.703		0.417	0.457		0.31		0.037	8.898	0.304	0.022	0.016	0.142		
PEL28	13.188	0.053	69.062	0.047	2.918		0.204		0.042	0.02	0.71		0.461	0.473		0.298	0.001	0.022	9.833		0.009		0.109		
PEL29	15.99	0.047	67.92		2.71	0.01	0.126			0.006	0.733	0.007	0.53	0.632	0.022	0.322		0.014	8.14	0.023	0.004		0.068		
PEL30	16.116	0.097	69.585		2.804		0.106			0.05	0.892	0.057	0.57	0.68		0.424	0.007	0.094	8.366		0.068	0.008	0.136		
PEL31	13.5	0.058	66.73		2.98	0.8	0.088	0.001		0.244	0.658	0.251	0.534	0.559	0.041	1.36	0.032	0.017	8.61		0.019		0.063	0.006	
PEL32	14.72	0.055	67.36		2.88	0.03	0.146				0.75		0.468	0.548	0.023	0.35	0.066	0.004	9.6		0.001		0.06	0.022	
PEL33	13.95	0.102	71.4		3.23	0.007	0.034	0.002		0.007	0.788	0.002	0.508	0.463	0.06	0.477		0.032	6.08	0.017			0.026		
PEL34	15.02	0.275	67.69		2.39		0.049	0.012			1.18	0.013	0.572	0.309	0.001	0.805	0.042	0.026	9.37	0.003	0.008		0.049	0.009	
PEL35	13.35	0.078	69.06		3.05	0.003	0.092	0.003		0.015	0.623	0.004	0.528	0.568	0.048	0.395			9.31		0.01		0.064	0.032	
PEL36	16.95	0.17	65.19		2.66		0.12	0.005		0.052	0.939		0.703	0.52	0.022	0.748	0.116	0.181	8.78	0.024	0.364		0.076	0.006	
PEL37	13.25	0.252	68.83		2.5	0.002	0.005	0.006		0.014	1.12	0.006	0.529	0.27		0.809	0.077	0.005	9.44	0.003	0.032		0.045	0.01	
PEL38	14.63	0.274	67.19		2.43	0.03	0.047	0.007	0.012	0.133	0.978	0.09	0.646	0.405	0.019	1.43		0.281	9.3	0.046			0.061	0.001	
PEL39	15.75	0.105	68.27		3.33		0.092	0.008	0.001		1.06		0.576	0.405	0.023	0.489	0.2	0.022	7.89	0.004			0.011		
PEL40	13.11	0.11	70.78		2.96	0.005	0.028	0.009		0.004	0.847	0.003	0.416	0.446		0.44	0.066	0.043	8.09	0.014			0.073	0.014	
PEL41	15.52	0.086	67.79		3.28	0.004	0.077	0.004			1.02	0.003	0.592	0.407	0.066	0.486	0.137	0.028	8.22				0.028	0.006	
PEL43	17.52	0.548	68.46		4.19	0.012	0.084			0.012	0.98	0.003	0.963	0.447	0.029	1.56	0.073	0.038	2.64	0.01	0.017		0.029	0.022	
PEL46	17.63	0.041	67.37		2.56	0.006	0.266			0.081	0.931	0.059	0.52	0.709	0.054	0.989	0.141	0.673	7.91	0.016			0.09	0.041	
PEL48	16.03	0.052	63.77		2.32	0.018	0.513	0.003	0.06	0.056	0.541	0.014	0.741	0.673	5.92	0.498		0.907	7.77	0.011			0.083	0.01	
PEL49	17.55	0.05	67.44		2.2	0.004	0.374			0.005	0.896		0.513	0.503	0.03	0.278	0.018	0.92	8.29	0.002	0.018		0.048	0.007	
Average	14.974	0.1514	68.415	0.0158	2.7213	0.0605	0.1103	0.0214	0.015	0.0406	0.9083	0.036	0.5855	0.538	0.1694	0.6493	0.0427	0.152	8.4921	0.033	0.0538	0.013	0.105	0.0124	
Std.	1.2573	0.1048	1.9164	0.0168	0.4163	0.1462	0.0923	0.0323	0.0185	0.0485	0.1629	0.0514	0.1883	0.2144	0.901	0.3669	0.0466	0.2473	1.2937	0.0658	0.0726	0.0156	0.0642	0.0112	

Table 5:Results of chemical analyses of natron glasses from Pella in oxide weight %. Blank spaces represent undetected oxides. Table includes the averages and standard deviations of this group.

Plant ash	Na2O	TiO2	SiO2	SnO2	Al2O3	ZnO	SO3	NiO	As2O5	CuO	Cl	CoO	MgO	K2O	Sb2O5	FeO	BaO	MnO	CaO	ZrO2	PbO	Cr2O3	P2O5	V2O3	SrO
PEL03	13.126	0.046	64.643	0.015	0.806		0.021	0.008	0.076	0.03	0.608	0.085	3.165	2.511		0.273	0.009	0.085	11.17			0.042	0.447		
PEL12	14.146	0.191	64.551		2.547	0.086	0.012			0.156	0.553	0.014	2.387	1.635		0.761	0.035	0.367	9.597		0.113	0.001	0.203		
PEL18	15.309	0.162	60.879		2.306	0.375	0.297		0.068	0.146	0.552	0.092	4.45	2.718		1.285		0.981	7.644		0.074		0.347		
PEL44	16.56	0.134	67.84		1.507	0.071	0.185	0.001	0.001	0.112	0.861	0.035	2.69	2.19	0.157	0.968	0.102	0.237	4.58	0.017	0.041		0.132	0.014	
Average	14.785	0.1333	64.478	0.0038	1.7915	0.133	0.1288	0.0023	0.0363	0.111	0.6435	0.0565	3.173	2.2635	0.0393	0.8218	0.0365	0.4175	8.2478	0.0043	0.057	0.0108	0.2823	0.0035	
Std.	1.2831	0.0543	2.4642	0.0065	0.687	0.1434	0.1191	0.0033	0.0359	0.0495	0.1276	0.0329	0.7877	0.4087	0.068	0.3677	0.0399	0.3403	2.4585	0.0074	0.0416	0.018	0.1227	0.0061	

Table 6: Results of chemical analyses of Plant ash glasses from Pella in oxide weight %. Blank spaces represent undetected oxides. Table includes the averages and standard deviations of this group.

Outliers	Na2O	TiO2	SiO2	SnO2	Al2O3	ZnO	SO3	NiO	As2O5	CuO	Cl	CoO	MgO	K2O	Sb2O5	FeO	BaO	MnO	CaO	ZrO2	PbO	Cr2O3	P2O5	V2O3	SrO
PEL45	15.23	0.013	67.98		0.673	1.81		0.008		1.7	0.105			7.05	0.784	0.038	0.11		4.25	0.035	0.029	0.419	0.031	0.012	
PEL47	16.16		67.92		0.643	1.65	0.029	0.012		1.68	0.092		0.002	5.77	0.719	0.045	0.039	0.005	4.19		0.004	0.413	0.001		
PEL48	16.96	0.048	62.81		1.139	6.67	0.271	0.003	0.007	0	0.016	0.003	0.19	5.81	0.422	0.026	0.245	0.163	2.76	0.006					
Average	16.117	0.0305	66.237		0.8183	3.3767	0.1	0.0077	0.0023	1.1267	0.071	0.001	0.064	6.21	0.6417	0.0363	0.1313	0.056	3.7333	0.0137	0.011	0.2773	0.0107	0.004	
Std.	0.7069	0.0175	2.4231		0.2271	2.3297	0.1215	0.0037	0.0033	0.7967	0.0393	0.0014	0.0891	0.5942	0.1576	0.0078	0.0854	0.0757	0.6887	0.0153	0.0128	0.1961	0.0144	0.0057	

Table 7: Results of chemical analyses of Outlier glasses from Pella in oxide weight %. Blank spaces represent undetected oxides. Table includes the averages and standard deviations of this group.

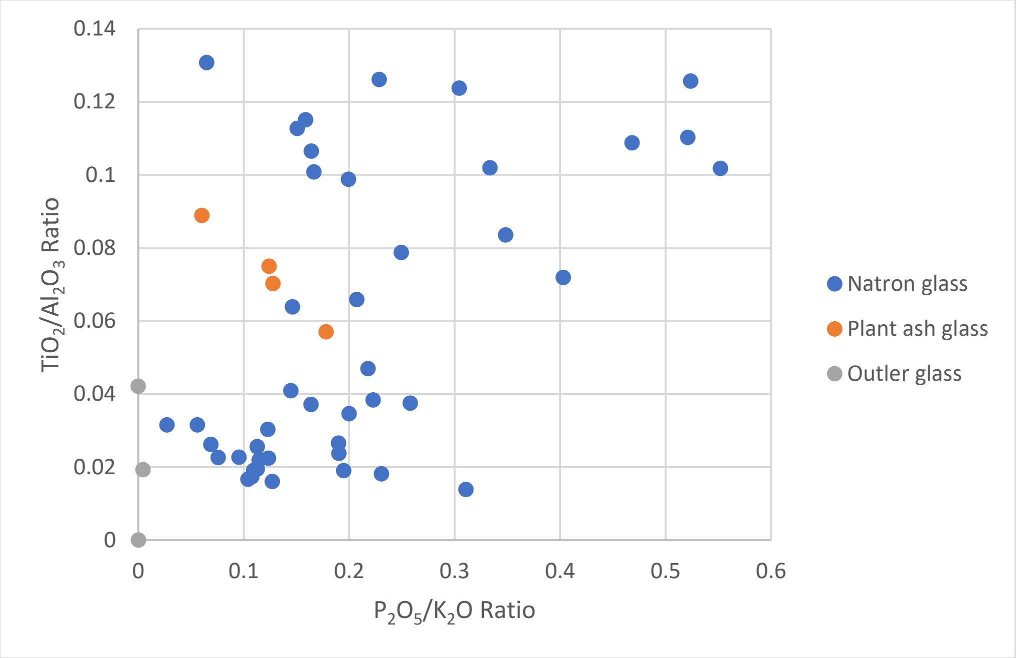

Figure 14: Biplot of the ratios of TiO_2/Al_2O_3 against P_2O_5/K_2O showing the separation of Pella natron, plant ash and outlier glass types and the glasses within

The glasses in the outlier group seen in Table 7 above show odd compositional qualities for Middle Eastern glasses. With an average CaO level of 3.73 wt%, there does not seem to be an alternative stabiliser. Woodash tends to provide sufficient calcium oxide to a glass melt but as this is lacking, these glasses may not be of the woodash type (Henderson 2013, 102–8; Wedepohl & Simon 2010). As well as this, these glasses have little amounts of metal impurities associated with silica sources such as FeO, TiO_2 and Al_2O_3, implying that a pure silica was probably used to make them. Strangely, the glasses appear to have a high amount of ZnO (greater than 1.5 wt%) with PEL48 even having a ZnO level of 6.67 wt%. No other research of contemporary ancient glass has composition similar to this and it is unknown what raw materials were used to produce such glass.

5.2.2. Colours of the Pella glasses

Most of the natron glasses from Pella are coloured blue-green which can be attributed to the “natural” colouring of Levantine raw glass at this time. Most of these glasses have similar compositions, though some with relatively high FeO compositions seem unaffected by its presence, though this is not unreasonable, furnace conditions may have been controlled in order to produce the blue-green colouration. The yellow and amber glasses also appear to have average compositions, with no prominent colourants or decolourants added. Standard levels of iron may have again resulted in this colouration, as perhaps different furnace conditions were used to produce this (Freestone & Stapleton 2015). There does not appear to be any correlation between the glass colours and the amounts of silica related impurities. The purer subgroup in Figures 13 and 14 seems to possess glasses of any colour, perhaps showing that the colouration of the glasses of Pella does not largely depend on the impurities present in them. Indeed, some samples of natron glasses show the use of decolourants. PEL48 shows a very high level of Sb_2O_5 at 5.92 wt% though does not seem to have lost its colour or be opaque as would be typical for such a great amount. None of the colourless natron glasses have significant amounts of MnO or Sb_2O_5 which are commonly seen in natron glasses (Freestone & Stapleton 2015). The red colour of PEL41 and PEL24 do not appear to have any noticeable colourants that could have introduced this colour, but it may be a product of controlled oxidation in a furnace as well. The deep blue colours of PEL14 and PEL38 do not appear to be produced by any detected colourant. Only a small amount of CoO can be attributed to cobalt blue colouration but neither of these glasses have a sufficient amount to make a noticeable effect (Adlington *et al.* 2020). Interestingly, PEL30 has a higher than average level of CoO at 0.25 wt% which could produce a strong deep blue colour but appears to be unaffected even though no decolourant was detected as well.

The plant ash glasses from Pella also appear to mostly be "naturally" coloured, the pale colours seem to have arisen from the impurities introduced in silicas mentioned previously. Slightly higher levels of MnO on average (0.42 wt%) suggest that some effort was made to decolour them but the natural blue-green or pale-yellow colours are still present. PEL18 has a deep blue colour but no obvious decolourant can be seen in its composition, perhaps a CuO level of 0.15 wt% may have brought this colour, but it is unlikely as other glasses with greater amounts of copper do not show as strong a colour. For their strange compositions, the outlier glasses show unremarkable colours. The pale colours of blue-green and yellow-green are fairly standard of Middle Eastern glasses but seem to not have been affected by such high levels of ZnO, and the higher level of CuO in PEL45 (1.70 wt%) also does not seem to have made a difference to the glass colour. PEL47 has a cobalt blue colour though no cobalt is present though it may have been a result of its CuO composition of 1.68 wt%. The outlier glasses seem to be a bit of a mystery and perhaps represent glasses made from an unknown technology in the Middle East at this time.

6. Discussion

6.1. Discussion of the natron glasses

The glasses that have been identified as being of the natron type from both Pella and Qasr al-Hayr al-Sharqi were compared to datasets of contemporary natron glasses of the Middle East. Comparisons were made with previously well-documented groups for natron glass, defined by their chemical compositions. The sites in which natron glasses have been found and that are used in this discussion are Bet Eli'ezer or Hadera, Apollonia and Khirbat al-Minya in modern day Israel; Yeroskipou, Maroni-Petrera and Kalavasos-Kopetra in Cyprus; various sites in Egypt; and al-Raqqa, Syria (Adlington *et al.* 2020; Ceglia *et al.* 2015; Henderson *et al.* 2004; Phelps *et al.* 2016; Schibille *et al.* 2019). Though not all of the glass types identified were produced in known primary glassmaking workshops, their chemical compositions have, however, been attributed to the geochemistry of important regions in the production of natron glass. These sites were chosen for their wide selection of glass types across many areas of importance in the Middle East and in order to provide insight about the distribution of glass to Pella and Qasr al-Hayr al-Sharqi. Data from this analysis was plotted on biplots with the data from the studies mentioned above, with the exception of the outlier type found in Pella as this did not appear to have any matching compositions.

As talked about previously, most natron glass was fused using mineral soda from a constricted region in the Middle East. Most of these glasses produced in the Middle East are likely to have used natron supplied from the Wadi el Natrun area in Egypt and therefore may demonstrate similar geological properties that are characteristic to this region. The analysis of the impurities associated with the soda source is unlikely to yield valuable information on the provenance of the soda source used to fuse these glasses. Indeed, when looking at the K_2O and MgO contents of the natron glasses of both sites, there is little variation. Perhaps the difference of mineral sources can be found through the use of more precise analysis such as that of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to see any trace element indications of geological provenance. However, one can discern differences from the sand sources used in the production of natron glasses (Schibille 2011). While natron may have been imported from one site, the sand used to produce the glass was likely gathered locally and major and minor components of the glass may reflect the region in which these sands originated from.

From Figure 15 we can see clear distinctions between different natron types when looking at the impurities related to the silica source. The high TiO_2/Al_2O_3 ratio is characteristic of Egyptian glasses showing perhaps that the sands from this region were less pure than those made in the Levant. It is suggested that this may be a result of Nile alluvium carrying heavier metal minerals from younger volcanic rock in Ethiopia (Henderson 2013, 331). As well as this, however, glass studied by Schibille *et al.* (2019) indicates that the compositions changed over time within Egypt, showing a difference in sand types resulting perhaps from different geographical locations of primary workshops. We can also see a homogeneity in

Levantine glass types which is likely a result of similar geochemistry of sands along the coast, though the variation in the Al_2O_3/SiO_2 ratio indicate perhaps the amount of feldspars in the sands used varied from location to location (Freestone 2006). This does not entirely separate the Levantine glasses, suggesting that the variation may just be an innate property of the sands in this region. The Egyptian glasses however can be differentiated along this axis, showing that the quality of the sands varied more drastically.

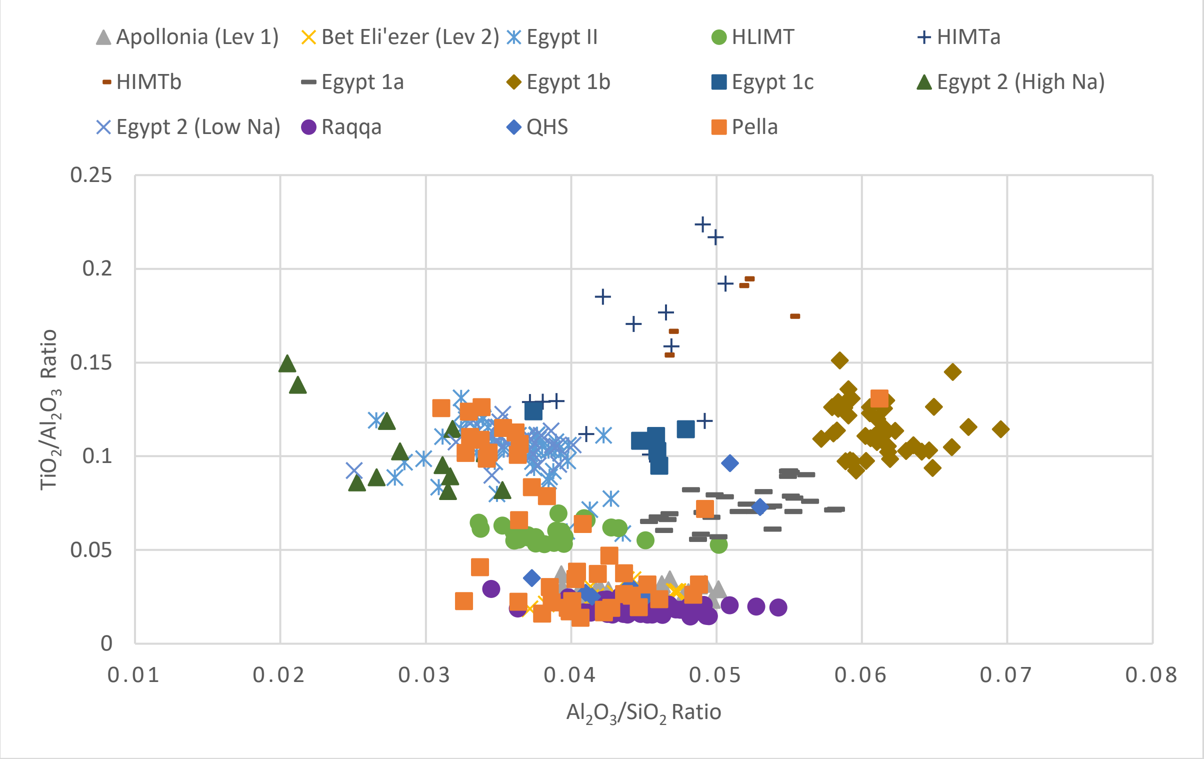

Figure 15: Comparative biplot of the ratios TiO_2/Al_2O_3 and Al_2O_3/SiO_2 for natron glasses from Egypt and the Levant

Of the Qasr al-Hayr al-Sharqi glasses, we can see that most of the glasses have low TiO_2/Al_2O_3 ratios, suggesting that they were made using a relatively pure silica source such those in Levantine groups. This is as expected considering the location of the site, as it is likely that glass would have been imported from settlements such as Palmyra with close links to the Levant. Two of the glasses (QHS05 and QHS07), however, have higher levels of this ratio and seem to fall into the "Egypt 1a" group outlined in Schibille *et al.* (2019). This shows that perhaps Qasr al-Hayr al-Sharqi was connected to the trade networks of the Eastern Mediterranean during its initial founding. "Egypt 1a" has been found to have been produced in the early 8th century CE which is consistent with the date of the founding of the site in the Umayyad period. Though this type of glass has also been found in later contexts (Schibille *et al.* 2019), therefore these fragments could have been brought to the settlement at a point later than the 8th century. The glass QHS07 does have a slightly higher TiO_2/Al_2O_3 than that of the "Egypt 1a" group but does not fall into any other Egyptian type which could indicate that perhaps this glass may be a result of intermixing between Egyptian glass types. Though this seems unlikely as there does seem to be little intermixing between natron glass types. It is worth noting that the natron glass found in al-Raqqa seems to be entirely made from the Levantine glass types, showing that even though its proximity to Qasr al-Hayr al-Sharqi is relatively close, none of the Egyptian glasses may have travelled beyond this site, indicating that the Qasr was tied more closely to the Levant than the Northern Syrian settlements had been. This could indicate perhaps the shift of Islamic centralisation to the East when the Abbasids took over, as Levantine glass would have been more easily available to Abbasid centres in Mesopotamia than Egyptian types. The fact that only two of these glasses had been found in Qasr al-Hayr al-Sharqi could just highlight the physical distance of these sites from Egyptian primary glass workshops.

Perhaps as less of a surprise, the natron glass found in Pella has a greater proportion of samples falling into Egyptian glass compositional groups. While Figure 15 shows that most of these glasses are of Levantine types, the most common Egyptian type is “Egypt 2”, consistent with the chronology of production outlined in Schibille *et al.* (2019) and the dating of the Pella glasses. This therefore reinforces that Pella was connected to the Middle Eastern glass trade at the time, a material that would have likely been available to the wealthy members of this settlement and many other settlements that were similarly in close proximity to major roads and trade routes. Though PEL43 has high Al_2O_3/SiO_2 and TiO_2/Al_2O_3 ratios characteristic of the “Egypt 1b” type, PEL07 of the “Egypt 1a” type are typically attributed to earlier dates than that of the glasses in this study. This could be due to the continued use of the glass since its initial introduction to the settlement a century prior or it could be the result of recycled glass melted in a local secondary glass workshop, especially considering the reduced supply of natron glasses occurring in the 9th and 10th centuries CE. As it is evident that older glass types had remerged after the initial circulation of glass weights in Schibille *et al.* (2019), perhaps this could explain the later appearances in Pella. Some of the older types could simply have been reintroduced to the glass trade for a brief amount of time as it had in Egypt. Only two natron glasses from Pella have these earlier glass compositions and in areas that are not in Egypt itself, perhaps the chronology of Schibille *et al.* (2019) glasses may not apply. Indeed, in Bet Eli’ezer, some “Egypt 2” glass can be found, albeit in small amounts (Phelps *et al.* 2016).

To analyse the Levantine glasses more thoroughly, Figure 16 was drawn to differentiate glass by the calcium oxide levels relative to alumina as well as the abundance of soda relative to the silica in the glass. The CaO/Al_2O_3 ratio indicates the amount of feldspar in the sand source as well as how much of the lime could have been provided by seashell fragments. The Na_2O/SiO_2 ratio is also used to provide insight into recipes of different batches, as limitations and differences in supply would affect these. As argued by Phelps *et al.* (2016), in the lower Na_2O/SiO_2 ratio of later “Bet Eli’ezer” glasses than those of the “Apollonia” type we can see the dwindling of natron glass export from Egypt, thus producing glasses likely more difficult to be worked. Also, we can see the lower Ca/Al ratios in Egyptian glass types, perhaps due to the geographical locations of their workshops. Workshops located within inland Egypt would have perhaps used less pure sands with greater feldspar content and had less access to calcium-rich coastal sands. Or perhaps, by using calcium-rich feldspars, the glasses would not have needed to rely on as much additional lime input from seashell fragments as the Levantine types would have. Though

"Egypt 2" type glasses have high CaO/Al_2O_3 values further supporting that different sites were used to produce the glasses.

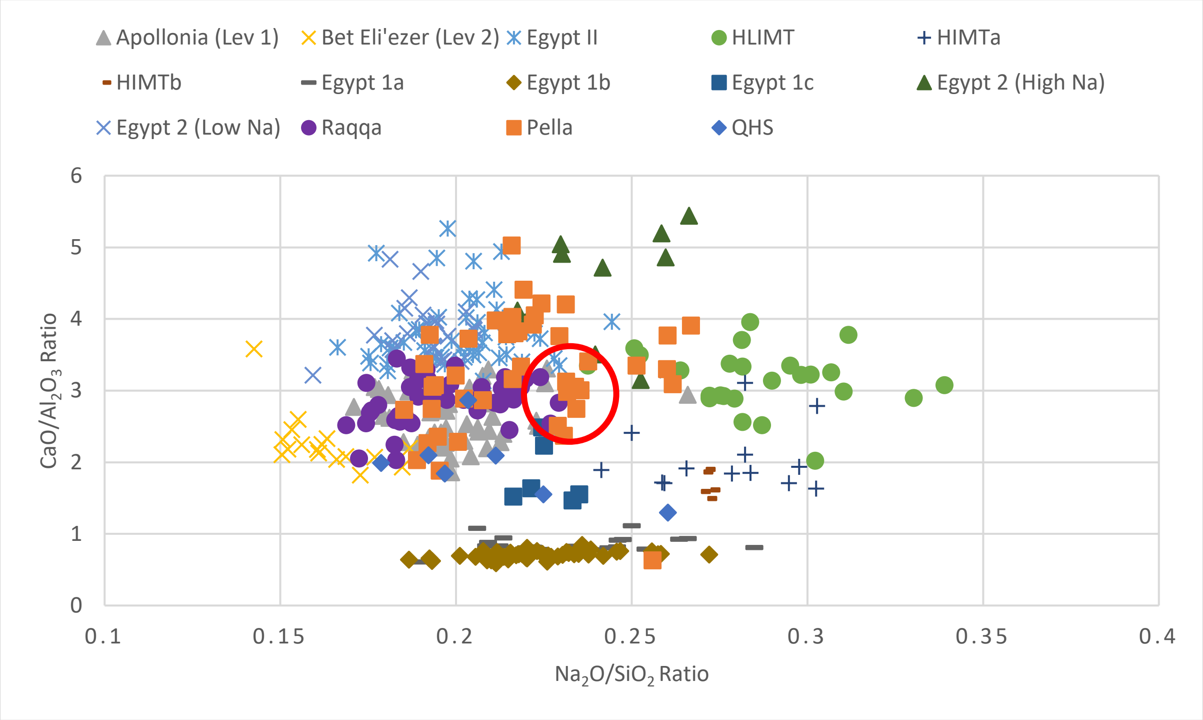

Figure 16: Comparative biplot of the ratios CaO/Al_2O_3 and Na_2O/SiO_2 for natron glasses from Egypt and the Levant including a group of glasses circled in red that may share a common origin.

As found previously the Qasr al-Hayr al-Sharqi glasses are primarily characteristic of Levantine glass types and indeed Figure 16 confirms that. Furthermore, all of these Levantine glasses fall into the Apollonia type glasses identified in Phelps *et al.* (2016), though at the lower end of the CaO/Al_2O_3 ratio range. In addition to the site's isolation and relative proximity to Apollonia, this could be indicative of a greater history of recycling of these glasses; however, it is hard to say certainly since calcium oxide levels could decrease due to a wide range of reasons as could an alumina level be increased. This link to recycling is tenuous at best since a location such as al-Raqqa is even more geographically distant from Apollonia and the Levantine glass compositions are even more varied. Though perhaps this variation could have also been a product of recycling and reuse, as glass in this region has been noted to have been produced using silica sources that are less calcium-rich than those found on the Levantine coast (Henderson 2013, 98–99). Local glass workers in al-Raqqa could have utilised nearby sands to add to batches of imported Levantine glass in order to have a greater volume of usable glass (Henderson *et al.* 2004).

The natron glasses of Pella in Figure 16 indicate a similar spread as previously shown in Figure 15 and it is evident that the glasses in the Levantine group are mostly of the "Apollonia" type. It is somewhat surprising to see that none of the Pella glass shows similar compositions to the "Bet Eli'ezer" type seeing its proximity to Pella and apparent importance during the short time it was active (Freestone *et al.* 2000; Phelps *et al.* 2016). Although, it is theorised that glass of that type was reserved for more local usage and perhaps was not traded as far as northern Jordan (Phelps *et al.* 2016). The Pella natron glasses that lie in Egyptian compositional groups are also fairly similar to that of Figure 15, though it is perhaps more evident in Figure 16 that some of the Pella glasses fall into the lower soda region of the “HLIMT” glasses outlined in Ceglia *et al.* (2015) which is also characteristic of some “Egypt 2” glasses. The prevalence of glasses of the “Egypt 2” type with respect to other Egyptian types found beyond Egypt could be indicative of changing trade patterns. As seen in Figure 16, the high CaO/Al_2O_3 ratio of later Egyptian “Egypt 2” glasses compared to those of the “Egypt 1” types could be a result of an increase in seashell fragment usage. This may be due to the movement of workshops closer to coastal regions where seashell fragments would be more abundant, suggesting greater availability for trade and distribution. Though there is no evidence of primary glassmaking workshops in Egypt during the Early Islamic period, and it is unknown what would cause the change in workshop sites seen at this time.

Additionally, circled in Figure 16, there is a tight group of glass that exists in a region unoccupied by any other natron glass (PEL05, PEL13, PEL29 and PEL30). This could be indicative of all of them being produced in a single glass melt and perhaps even from a unique and new primary production workshop though this seems unlikely. Multiple tight groups appear in Figure 16, and while they may indicate individual glass melts, there is not enough evidence to support that they are from new production centres. While no contemporary glass workshop has been found at Pella, a history of secondary glass production is known here and perhaps there was a continued glass industry nearby. Seeing as this tight group share a unique composition, it may have only been used for local demand as other secondary glass working sites could have done. Though similar in composition, not all elemental oxides share the same values in this analysis and more precise measurement is needed in order to find exactly how similar these glasses are. Early Islamic natron glass analysis is very incomplete at this stage and requires much more study to be sure about the origin of these glasses.

In Figure 17, impurities that would have been introduced from silica sources are compared in order to differentiate the geochemical signatures of natron glasses, this time focusing on the iron oxide presence. The ratio FeO/TiO_2 was plotted against FeO/Al_2O_3 with the anomalous results of PEL31 and PEL46 omitted in order to prevent the display of data from being distorted. A further use of this biplot can help assist in discerning whether any recycling took place. As outlined in Barfod *et al.* (2018), repeatedly recycled glass is likely to have accumulated impurities from the equipment used to produce it, including iron glass working tools. So, one should expect from a biplot such as Figure 17, to display a general positive correlation. Indeed, for both Levantine and Egyptian glass groups, one can see glasses separating from the main groups in different directions to the general trends of the main groups. For example, with the main group of Egyptian glasses, a general negative correlation can be observed except for some glass samples branching off in a general positive correlation away from the origin. Though one cannot say for certain if these are the result of repeated recycling or just an artifact of other external factors affecting glass composition, and it is impossible to know to what extent these glasses were recycled. More accurate analyses can be used to detect the extent of glass recycling such as trace element and isotopic analysis; detection of minuscule amounts of trace elements and their isotopic counterparts can give a clearer indication of the nature and amount of what gets added to a glass batch during the remelting and reworking process (Degryse *et al.* 2006; Freestone 2015; Rehren & Freestone 2015). Furthermore, statistical methods such as Principal Component Analysis (PCA) could be used to group glass types using a more complex and multi-dimensional approach, perhaps highlighting similarities in glass compositions that would indicate a shared origin like that of a singular batch or glass workshop (Ceglia *et al.* 2019; Phelps *et al.* 2016; Schibille *et al.* 2012).

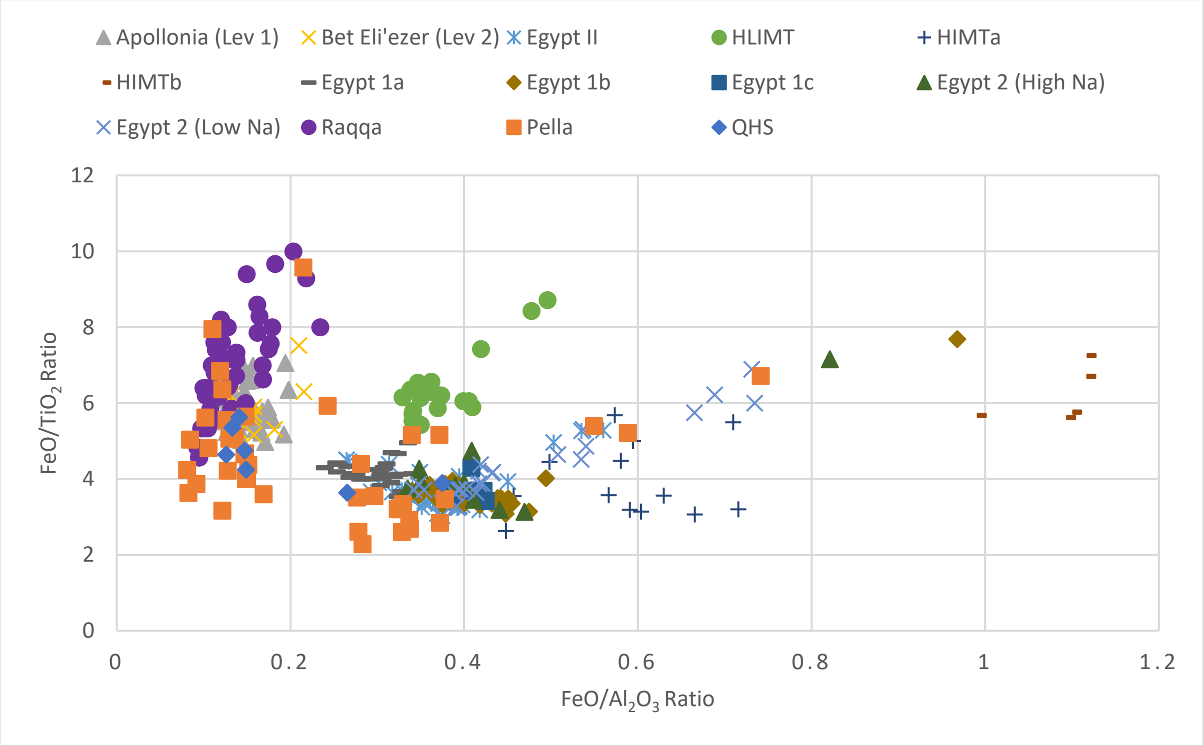

Figure 17: Comparative biplot of the ratios FeO/TiO$_2$ and FeO/Al$_2$O$_3$ for natron glasses from Egypt and the Levant

While Qasr al-Hayr al-Sharqi natron glasses conform relatively well to the groups mentioned previously, there are a few interesting features to note for the glasses from Pella. Of those from the Egyptian glass types, many have low FeO/TiO$_2$ ratios relative to the rest of the group, showing that relatively pure sands may have been used to fuse them. The same can also be said about a number of glasses in the Levantine group. This may align with the claim that some of the glass may have originated from unique melts nearby to the site of Pella and thus saw too little recycling to introduce great amounts of impurities. Or perhaps a disproportionate amount of titanium oxide could have been introduced into these glasses if they were remelted at this site. It is impossible to say what may have caused these deviations but it is clear that the glasses found at Pella may not fall perfectly into the previously defined compositional groups and more research and excavation is needed in order to paint a clearer image of glass working at this site. The presence of the anomalous glass compositions could even be an indicator of experimentation on glass, adding materials not typically used in glassmaking processes at the time. We also see the deviation of al-Raqqa glasses from the Levantine glass compositions, thus further indicating that the nature of natron glass production and distribution is more complex than what these studies have been able to find out so far. Indeed, the deviations from the main groups could be indicative of further glass production in sites defined beyond the known compositional groups of the literature or even a sign of different practices in the secondary glass working stage. While natron glass analysis is perhaps more extensive in Byzantine contexts, these findings ask more questions about Early Islamic glass production and how it may have begun to change towards the end of natron glass technologies in the Middle East.

6.2. Discussion of the plant ash glasses

The glass that has been identified as plant ash glass from Qasr al-Hayr al-Sharqi and Pella was compared against contemporary datasets of plant ash glasses throughout the Middle East and along the Silk Road. The sites in which plant ash glasses were found and studied are Tyre and Beirut in the Lebanon; Khirbet al-Minya in modern day Israel; Cairo, Egypt; Damascus and al-Raqqa in Syria; Ctesiphon, Samarra and Veh Ardašīr in Iraq; Nishapur, Iran; and Ghazni in Afghanistan (Fiorentino *et al.* 2019; Henderson *et al.* 2004; 2016; Mirti *et al.* 2008; 2009; Phelps 2018; Schibille *et al.* 2018). These were selected due to the importance of these sites during the Early Islamic period and the wide range of land that they cover in order to best characterise the glass from the sites of this analysis. Though Mirti *et al.* (2008; 2009) focus on Sasanian glass fused before the Islamic conquest, they were included in order to gain insight into how plant ash glass may have influenced the production of those found at Qasr al-Hayr al-Sharqi.

Plant ash compositions can be a lot more varied than natron types, due to the variability of the raw materials used to make them. When making plant ash, the plants used for the soda source can contribute different impurities to the glass chemistry relative to the geology of the land that they grew on as well as the method by which the glass was fused. As was the case in natron glass, the geochemistry of the silica source can also affect the composition of plant ash glass. Though the compositions are varied, it is possible to find regional trends and even distinct signatures attributed to regional subzones as demonstrated in Henderson *et al.* (2016). Figure 18 indicates the broad differences in composition of many glasses across the Middle East. Glass produced in Iran and Mesopotamia tend to have higher MgO levels and lower CaO levels, while that which was fused in the Levant and Egypt typically has lower MgO levels and higher CaO levels. The lines included in Figure 18 also enclose glasses mostly from Northern Syria such as that from al-Raqqa (Henderson *et al.* 2016). Though overlap is great between these regions, there is a general trend of compositions, even with earlier glasses produced by the Sasanians. The plant ash glasses from Qasr al-Hayr al-Sharqi generally appear to be from North Syrian regions of production though some overlap with the Levantine compositions could suggest a more western origin. As al-Raqqa appears to be one of the first production centres of Islamic plant ash glass, it is a likely origin for the glasses found at the Qasr due to the proximity of the two sites and their dating. Two of the plant ash glasses from Pella fall into the Levantine glass compositional group and the other two appear to be in the Mesopotamian and Iranian group. The Levantine origins are of no surprise given Pella's location and connection to local trade routes. As natron glass had likely been imported into Pella, plant ash glass could have too. Though since the amount of plant ash glass relative to natron glass found at Pella is small, its production and distribution was likely minimal in the Levant where natron glass was still available. Although, looking at the chronology of glass types at the nearby site of Ramla, we can see that plant ash glass types were dominating the scene from the 9th century CE onwards. It is then unusual to see so little plant ash glass in Pella at this time. Perhaps what was excavated could be a glimpse into the turning point between these two glass technologies. Though it appears that no glass travelled from Northern Syria, more local glass workshops in the Levant may have just started to produce plant ash glasses for distribution. This could also demonstrate the interconnectedness of Pella to the Silk Road and to the Far East; glass may have been travelling across the Syrian desert from Mesopotamia among other goods.

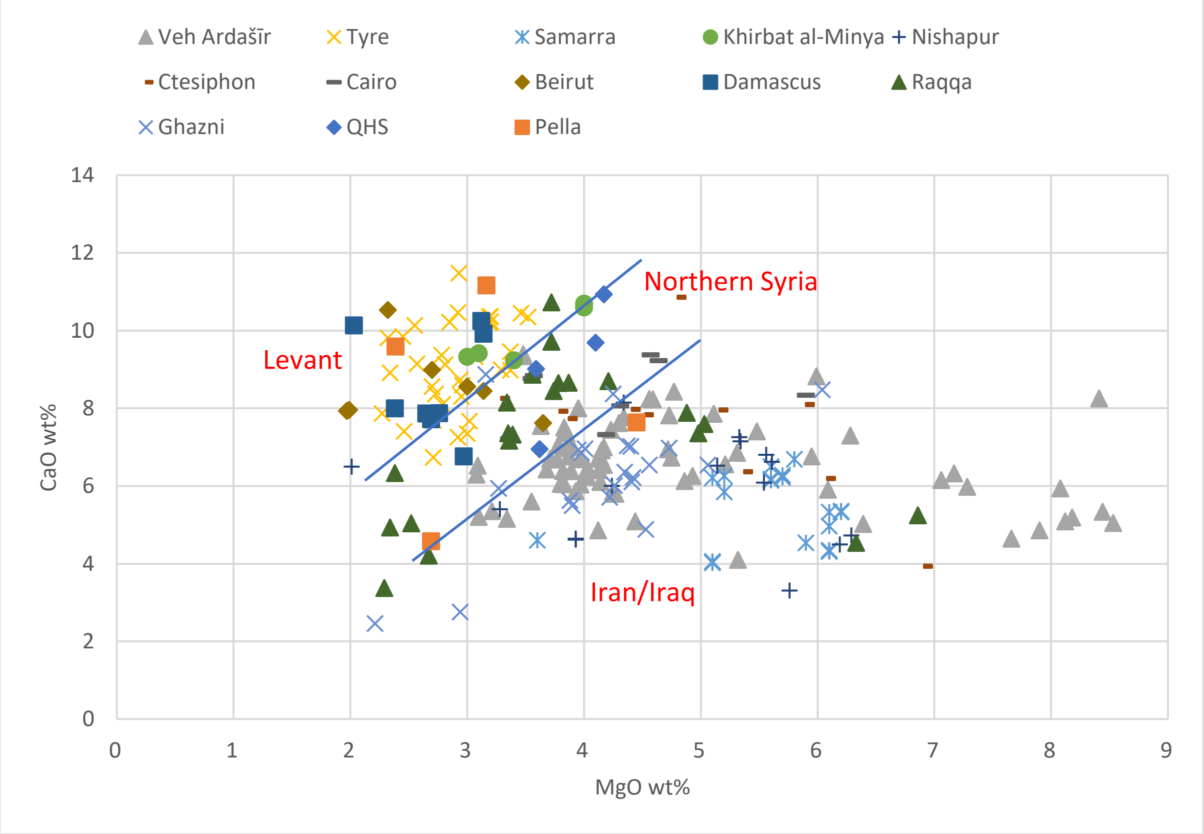

Figure 18: Comparative biplot of CaO and MgO wt% for plant ash glasses from across the Middle East. Including lines to assist in differentiating broad production zones derived from Henderson et al. *(2016) and labelled as: Levant, Northern Syria and Iran/Iraq.*

Figure 19 also incorporates alumina levels when analysing the glass compositions, differentiating sand types against plant ash contributions represented as the ratio MgO/CaO. While there is much overlap between regional glass compositions as seen before, figure further affirms the origins of the Pella glasses. It is also evident that the Qasr al-Hayr al-Sharqi glasses were perhaps produced as part of the experimental glass working phase of al-Raqqa (Henderson *et al.* 2004). Given how early the dating of these glasses are, it would make sense that they were produced during a time of new technological innovation, coinciding with the "re-invention" of plant ash glasses in the Middle East. It is likely why we see both natron and plant ash glasses at this site as it could have been seeing just the beginning of the transition between them. During its early occupation, the Qasr would likely have housed the elite of Early Islamic society and therefore it may be no surprise that the new and probably high valued glass from al-Raqqa had accompanied some of those who travelled here.

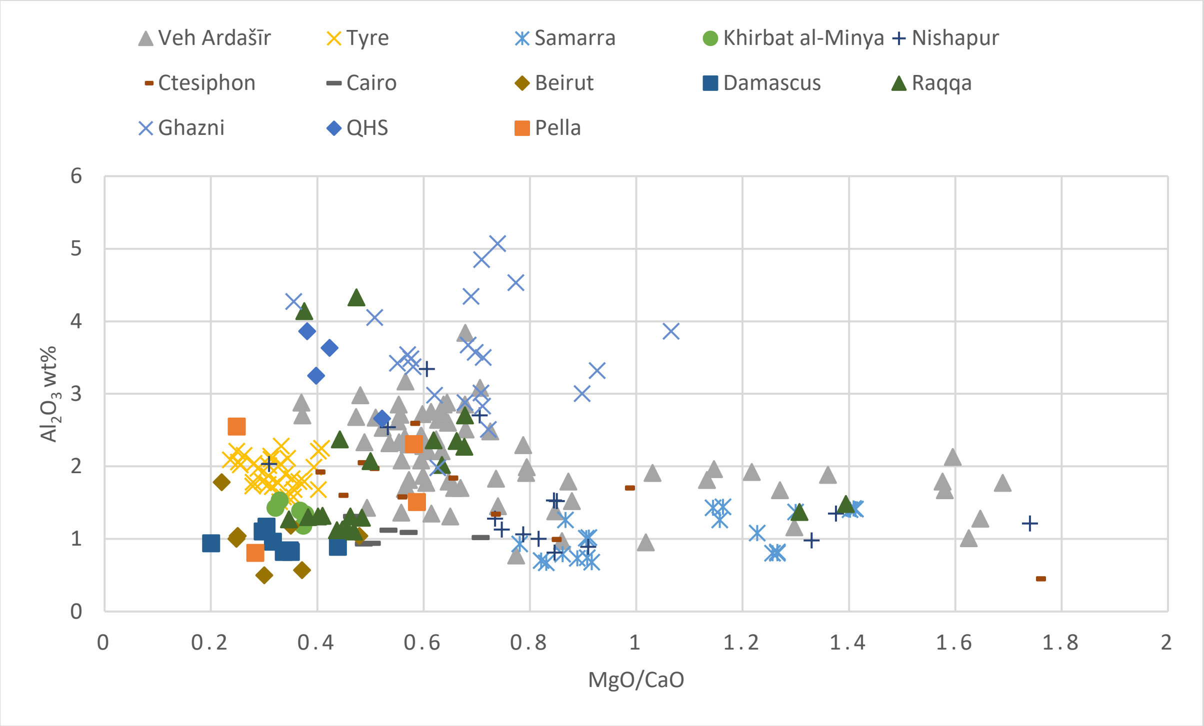

Figure 19: Comparative biplot of Al_2O_3 wt% and the ratio MgO/CaO for plant ash glasses from across the Middle East

The ratios of FeO/Al_2O_3 and P_2O_5/K_2O were plotted against each other in order to compare relative silica source purity with plant ash purity in Figure 19. We can see further distinct compositional groups for sub regional centres such as those from Mesopotamia but also broader groups from that of al-Raqqa and the Levantine production centres. Though the broad groups make it difficult to define where the glass raw materials had originated from, it can be seen that one glass from Pella and one from Qasr al-Hayr al-Sharqi each have relatively pure soda and silica sources. The wide distribution of al-Raqqa glasses in this Figure 19 could perhaps be an indication of the experimentation that occurred to produce some of this glass, though three of the Qasr al-Hayr al-Sharqi glasses remained near al-Raqqa compositions, maybe due to them being the results of a similar batch. It is not possible to link these glasses as such, seeing as how they are so varied in their compositions and have no other examples of similar glass. We also see the proximity of Pella glasses to Levantine types, indicating perhaps a similar source of raw materials, but the variation is too great to determine this. One Pella glass from Mesopotamia shows a relatively high FeO/Al_2O_3 ratio which may indicate that it also originated from an experimental batch, though there are no similar compositions, bar one Sasanian sample. Thus, this shows us that more research is needed in order to improve the picture of how plant ash glass travelled across the Middle East. The variation in purities of these select glasses could exemplify this transition between the technologies of natron and plant ash glass, where different recipes were being experimented within major Islamic population centres. Although, there are too few samples to be able to make any definite estimates of their provenance or to see if their differences are a result of experimentation or rather just indication of different regional glassmaking practices. Furthermore, apart from al-Raqqa, no other inland primary plant ash glass production sites have been found and therefore there is little physical evidence for experimentation in other places. Like in al-Raqqa, if it did occur, experimental glasses would see little movement outside of the region of production. If the plant ash glass found at Qasr al-Hayr al-Sharqi is a result of this experimentation, they would likely have been brought by the most elite of society, perhaps even by the caliph himself if he travelled south from al-Raqqa. This can be inferred by the fact that many of these experimental types were used in palatial contexts (Henderson *et al.* 2004). Perhaps it could even be the result of experimental glasses from other possible glassmaking centres travelling with the Islamic nobility. This leaves a promising future for plant ash glass analysis along the Silk Road but much more excavation and scientific analysis is needed in order to explore further than what is already known. Perhaps future evidence of primary glass production and subsequent exchange can pave the way for a clearer image of the Early Islamic Middle East.

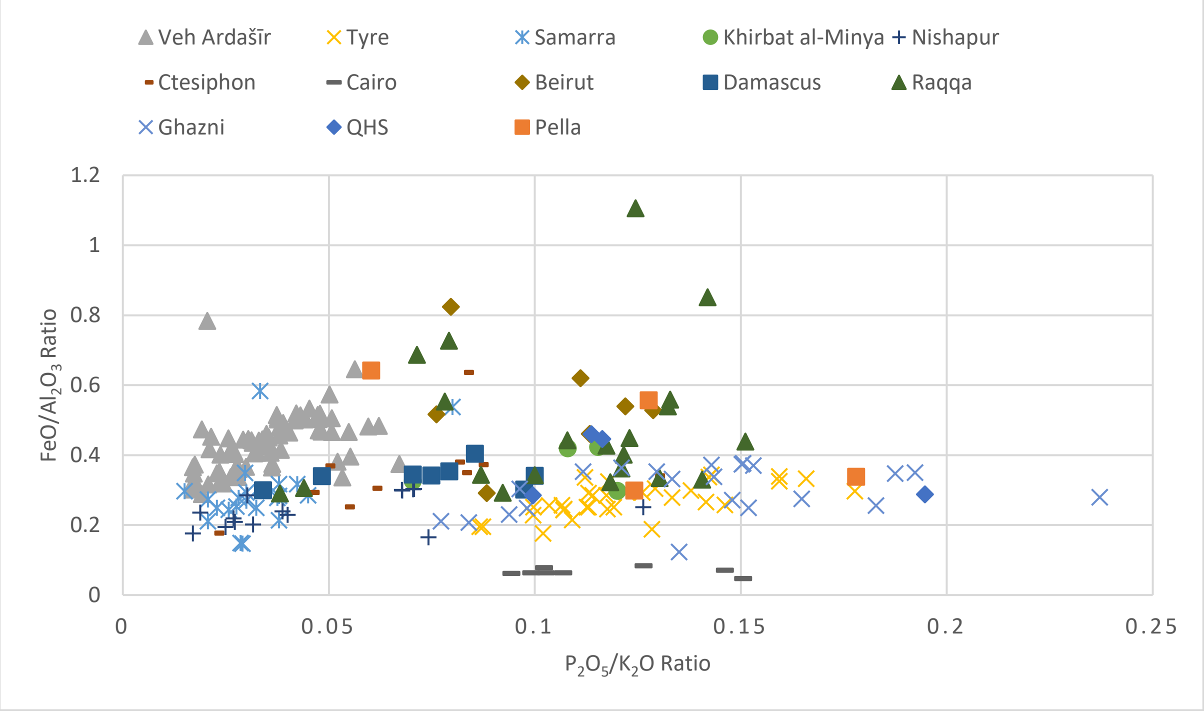

Figure 20: Comparative biplot of the ratios FeO/Al$_2$O$_3$ and P$_2$O$_5$/K$_2$O of plant ash glasses from across the Middle East

7. Conclusions

Major and minor element analysis has characterised glass from the Levantine site of Pella and the Syrian desert castle of Qasr al-Hayr al-Sharqi to known compositional groups found throughout the Middle East, providing insight into regional production zones and how glass may have travelled along the Silk Road. Furthermore, the analysis of such glass has offered a glimpse into the transitional period between the Eastern Mediterranean natron glass production and the more geographically widespread Islamic plant ash glassmaking. Through the comparison with contemporaneous glass finds from the Middle East and their major and minor oxide components, insights into the production and distribution of literature-defined compositional groups can be made.

It was found that the glasses from Qasr al-Hayr al-Sharqi could be compositionally defined as soda-lime-silica of both the natron and plant ash types. The natron glasses being defined as having low MgO and K_2O components could be further differentiated by their minor element oxide components which reflect the geochemistry of the materials used to fuse them. Glasses with high levels of metal impurities such as FeO and Ti_2O were found to be compositionally similar to Egyptian glass, reflecting the less pure sands likely used to fuse them (Schibille *et al.* 2019). Most of the natron glass at Qasr al-Hayr al-Sharqi, however, had compositions similar to that of the Levantine Apollonia type defined by by Freestone *et al.* (2008) and Phelps *et al.* (2016). The presence of these glass compositions shows the degree at which the site was connected to trade networks during the Early Islamic periods, the occupants of which being able to obtain goods from as far as Egypt.

The site of Pella also contained glass of both natron and plant ash types, though also a third undefined group of anomalous composition has been found. The natron glasses also displayed compositions like that of glass from both Egypt and the Levantine Coast such as those of the HLIMT and Egypt 2 types described by Ceglia *et al.* (2015) and Schibille *et al.* (2019) as well as the Levantine 1 or Apollonia type characterised by Freestone *et al.* (2008) and Phelps *et al.* (2016). Smaller collections of similar glass compositions within these types may also have even indicated on-site glass working, potentially using methods different to that of Palestine or Lebanon on the other side of the Jordan Valley. Despite this, Pella most likely saw glass imports from the glassmaking regions of Egypt and the Levantine coast, perhaps expected due to its location and evidence of a well-connected urban society.

As the recycling and remelting of glass can have a number of minute effects on their compositions it is hard to say to what extent these glasses had been recycled, though it is likely that some natron glasses from both sites had experienced recycling to some degree. As the export of glass from primary glass working sites would typically come in the form of glass cullet, secondary glass workshops such as that found previously in Pella would have had to be melted down in order to work it into a useable form. As no such glass working sites have been found at Qasr al-Hayr al-Sharqi, little can be said for whether these natron glasses were ever remelted and worked here and further research is needed to be able to accurately determine the characteristics of recycled glass in major and minor element oxide compositions.

The plant ash glasses were characterised as having high levels of MgO and K_2O and would have compositional groups found similarly to the natron types, though impurities introduced by both the plant ashes and sands could be analysed in this case. The plant ash glasses from Qasr al-Hayr al-Sharqi had compositions that fell into the broad Northern

Syrian production zone, perhaps originating from al-Raqqa just to the north of the site. The wide variation of plant ash glass compositions made it difficult to define any specific site but due to its early context these finds could indicate the export of experimental plant ash glasses from the Early Islamic plant ash industry of al-Raqqa.

Pella’s plant ash glasses showed compositions similar to that of the broad Levantine and Egyptian regional groups as well as that of Iran and Iraq. Again, while the variation is great in the compositional groups, these finds may show the continued trade of glass into Pella following the transition into plant ash technologies. Iranian or Iraqi origins of some of this glass may also indicate Pella’s presence on the Silk Road, perhaps as an important stopping point between the eastern and western regions of the relatively new Islamic caliphate.

Even though this research opens up more questions about the interconnectedness of the Early Islamic glass trade along the Silk Road, further research must be conducted in order to produce a clearer image into how glass was produced and travelled. The research of the glasses would benefit greatly through the use of more precise techniques such as that of laser ablation inductively coupled mass spectrometry in order to discover their trace element profiles. With both natron and plant ash glass, trace element analysis could be used to discover a more exact provenance of the raw materials used to produce them as well as find the extent to which recycling occurred. Furthermore, isotope analysis of glass could be used to find the geological age of the raw materials used to make them, thus providing an even clearer provenance when paired with the analyses mentioned above.

This research has been able to identify the movement of plant ash glasses along the Silk Road during the Early Islamic period. As well as seeing the inland distribution of natron glasses produced in Egypt and the Levant, some of the earliest cases of plant ash glass trade have been identified in Qasr al-Hayr al-Sharqi. Sites such as Pella and Qasr al-Hayr al-Sharqi are just two stops bridging the gap between the East and the West along ancient trade networks of the Middle East and this research demonstrates how significantly interconnected these two hemispheres were.

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