# Composition and Origin of the First Millennium AD Glass Uncovered at Khirbet adh-Dharih, South Jordan.

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## Abstract

Sixty-four glasses excavated at Khirbet adh-Dharih, south Jordan, and archaeologically dated from the Roman to Early Abbasid periods were analyzed by wavelength-dispersive electron probe microanalysis (EPMA). The majority of the glasses (57) were fluxed with natron. In the Roman period antimony-decolorized glass from Egypt, manganese-decolorised glass from the Levant and recycled Roman MnSb glass are present. From the middle of the fourth century glass from the Levantine production centers Jalame and Apollonia dominates the assemblage up to the eighth century, when glass from Bet Eli'ezer becomes common, consistent with previous findings from the North. Egypt I and II types also occur at this time, consistent with previous findings from the wider region indicating that Egyptian glass continued to be imported into the Levant in the 8-9$^{th}$ centuries. Plant ash glass is represented from Mesopotamia, from Tyre and from unidentified sources in Egypt or Syria. Overall, these results suggest that glass from a wider range of sources was being exploited in the early Islamic period than in Byzantine times. Evidence for recycling is particularly apparent in the Apollonia-type glasses but is hardly noticed in the Bet Eli'ezer-type, consistent with a greater dependency on local resources in the sixth-seventh centuries.

**Keywords**: Natron glass, Plant ash glass, Egypt glass, Levant glass, Recycling, Mixing, Contamination, Khirbet adh-Dharih, South Jordan.

## 1. Introduction

The archaeological site of Khirbet adh-Dharih is located in the governorate of Tafilah, south Jordan, about 70km to the north of Petra (Fig 1. Map). Because of its location along the King's Highway, on the eastern bank of El-La'ban valley, and nearby three springs, the site was an agricultural center and an important station for the caravan trade between Petra and Bostra (al-Muheisen and Villeneuve 1988). The Neolithic pottery, and Edomite, Nabatean, Roman, late Byzantine and Islamic

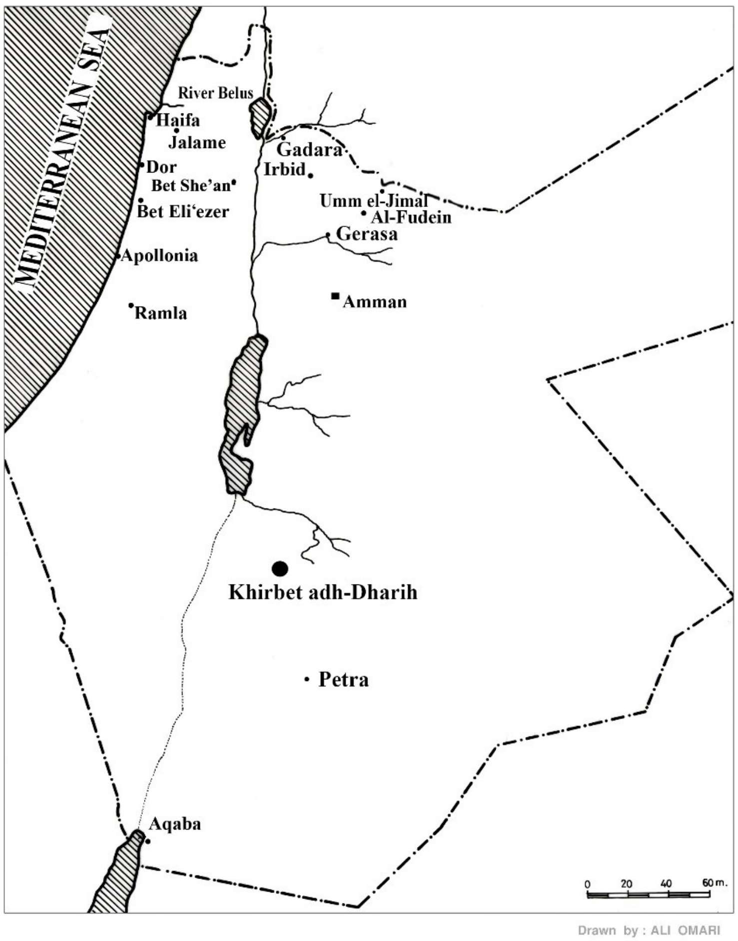


Fig. 1. Location map of Khirbet adh-Dharih and other sites mentioned in the text.

pottery and other archaeological remains indicate that the site was settled from the Pottery Neolithic PNA period (al-Muheisen and Villeneuve 2005). The presence of the largest Nabatean sanctuary uncovered outside Petra at Khirbet adh-Dharih indicates its stateliness and prosperity during the Nabatean period. It achieved its most significant phase of development during the Roman periods (Villeneuve and al-Muheisen 2008); but it continued to thrive during the Late Byzantine and Islamic periods (Villeneuve 2011). Although its main preserved building is the sanctuary, it has more than twenty buildings, farmers' dwellings, a luxurious house, oil presses, baths and several cemeteries (Fig.2), (al-Muheisen and Villeneuve 2005, Sartori 2015).

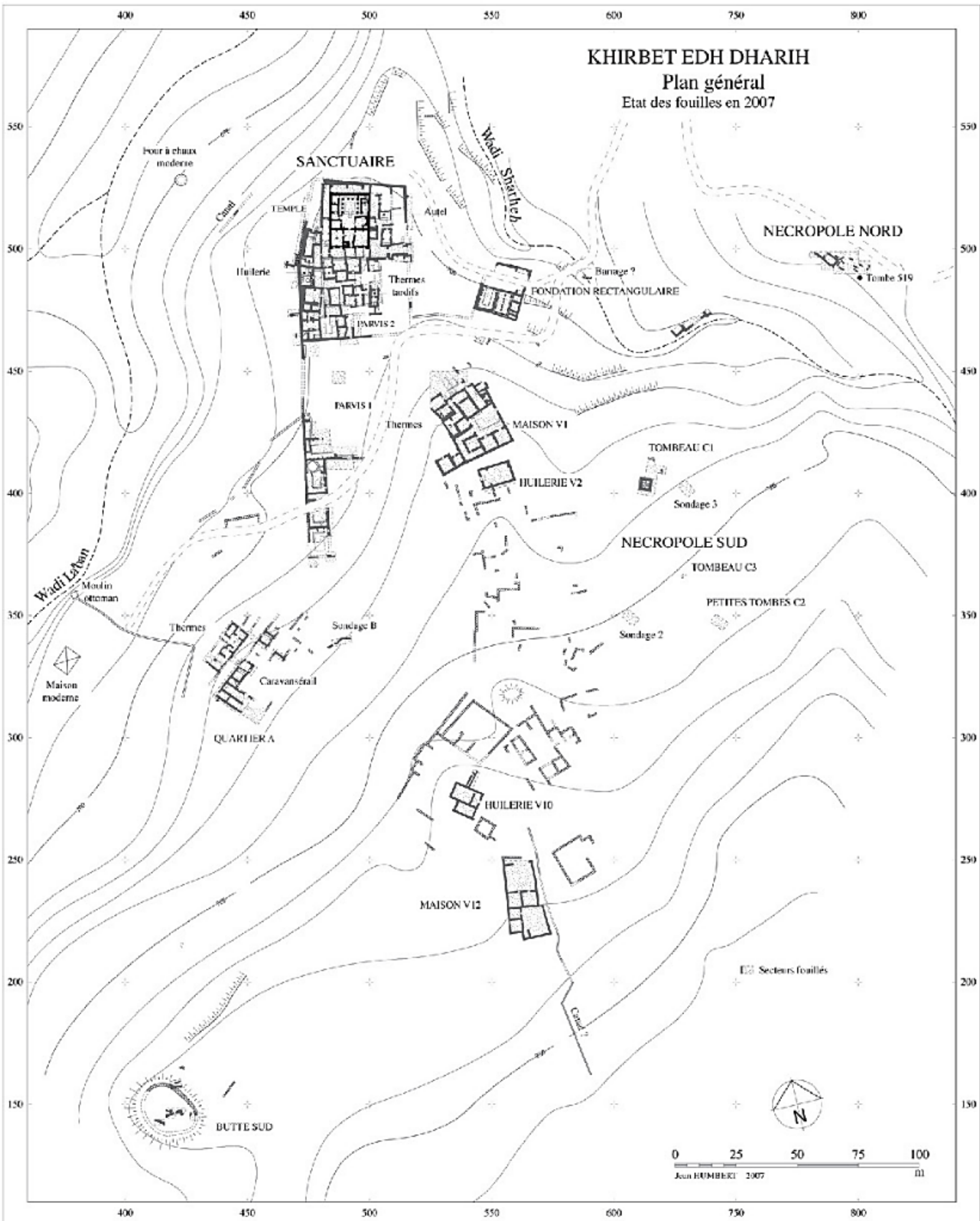

Fig.2. General map of Khirbet adh-Dharih (After Al Muheissen and Villeneuve 2013:Fig. II.12).

Excavations, that started in 1984, uncovered a wide variety of archaeological remains including a large number of glass fragments from contexts dating from the Nabatean ($4^{th}$ c. BC- AD 106 AD), Roman (63BC – 324 AD), Byzantine (324 AD – 636 AD) up to the Islamic periods starting from 636 AD (Table 1) (Dussart 2007). The glass collection, found in different areas and structures, consists mostly of tableware including beakers, bowls, bottles, goblets, juglets, etc. and bracelets.

It is now well agreed that glass production underwent a number of significant compositional changes during the $1^{st}$ millennium AD and a number of glass compositional groups of different primary workshops have been identified in Late Antiquity and the Early Islamic periods (Cholakova et al 2015; Cholakova and Rehren 2018; Freestone et al. 2018, 2023; Schibille et al. 2019; Foy et al., 2003). In addition, it has been shown that secondary workshop processes such as glass reuse, glass mixing, contamination and loss of volatiles at high temperatures of ancient glass caused a number of compositional changes during glass production (Al-Bashaireh et al. 2016a, Barfod et al. 2022, Freestone et al. 2015, Tal et al., 2008; Paynter, 2008; Rehren et al., 2010).

The study of the Dharih glass collection provides an opportunity to better understand the changes of glass composition, workshop processes and the distribution of archaeological glass during a long period of time of the $1^{st}$ millennium AD. It will also permit the comparison of glass distribution at Khirbet adh Dharih to other sites of similar date in north and east Jordan. It uses standard approaches to classify the studied glasses to their major production groups that were recognized in the past decades.

**2. Dating the glass collection:**

The glass collection was dated based on the stratigraphy, radiocarbon dates, accompanied pottery and coins, and the contexts of the glass. Excluding a very few loci from lower strata and the upper deposits from the Medieval period (around the $10^{th}$ cent.) that did not contain glass, the areas S2, S3, S4, S5, S6, S8, S9, S10, S11, i.e. the temple and the northern courtyard of the sanctuary around the temple, were continuously reused from the $6^{th}$ till the $8^{th}$ cent. AD. Consequently, the glasses from these areas were dated to the $6^{th}$-$8^{th}$ cent. AD. This date was confirmed by dates of the accompanied abundant remains of pottery and radiocarbon dates of seeds and bones from the same strata, occasionally charcoals (Waliszewski 2001). Other areas at Dharih (S1, S7, V, FR) were used neither during the $6^{th}$ cent. nor during later periods, which most likely indicate that they were abandoned after the 363 AD earthquake. Because the foundation levels of the buildings at these areas were erected around 100 AD (except few strata that can be dated to the $1^{st}$ cent., in V10 for example), all the glasses from these areas were dated from the $2^{nd}$ to the $4^{th}$ centuries AD. More precise dates to the $2^{nd}$ and $3^{rd}$ centuries AD were given to area A based on its content of coins and pottery. Similarly, area S7 at the entrance of the sanctuary was dated to the $3^{rd}$ cent. AD exclusively, depending on its content of sealed pottery fragments and coins. Context numbers for the objects analysed are provided in Table 1/Supp. Table 1. While we are reasonably confident in the stratigraphic contexts of the samples, inevitably some intrusive and/or residual samples are apparent, see below.

**3. Materials and methods**

A set of 64 glass samples of different shapes, functions, colors and decorations was selected for this archaeometric investigation. Descriptions, profile illustrations and photographs of each object are provided in Supplementary Table X. The analysed assemblage mainly comprises blown vessels in “naturally-” or “weakly-coloured” glass. Several samples are in strong blue, and several are amber. Several bracelet fragments are also present. The samples cover a long span of time from the Roman (63 BC – 324 AD) till Umayyad (661 AD – 750 AD) – early Abbasid (750 AD – AD 900 AD) Periods, one fragment (of indeterminate form) was probably of the Nabatean ($4^{th}$ c. BC – 106 AD) period.

Chemical analyses were performed at the Institute of Archaeology, UCL using a JEOL JXA 8100 microprobe with three wavelength-dispersive spectrometers, operated at 15 kV accelerating potential, beam current 50 nA, working distance of 10 mm and rastered at a magnification of x800. The samples were prepared for analysis by cutting 2-4 $mm^2$ from each sample, mounting them in epoxy resin and exposing their fresh cross sections using silicon carbide papers, and then polishing them with diamond pastes down to 1 µm. Finally, they were vacuum coated with a thin carbon layer in preparation for electron probe microanalysis (EPMA) with wavelength-dispersive spectrometry (WDS). X-rays were collected for 30 s on peak and 10 s on each background. Standards were pure elements, oxides and minerals of known composition. Three areas were analyzed on each sample and the mean was taken. Corning Museum Ancient Glass Standards A and B (Brill 1999, Vicenzi et al. 2002, Wagner et al. 2012) were measured eighteen times during analysis, and the measurements compare well with the given values for most elements (Table 2, supplementary materials).

## 4. Results

EPMA results are presented in Table 2 (supplementary materials). They show that all the samples are soda-lime-silica glasses. 57 glasses are of the natron type with low $K_2O$ and MgO, while seven (DHL 1, 4, 6, 15, 16, 17, 18) are of the plant ash type with $K_2O$ and MgO in excess of 1.5% (e.g. Brill 1970, Lilyquist et al. 1993) where the ash was the source of soda.

Bracelet samples DHL5 and DHL 10 appear to have been made using mineral soda, but have elevated $K_2O$, from 1.5-2.6%. This type of glass has previously been observed in bracelets from Jordan (Al-Bashaireh 2016, Boulogne and Henderson 2009, Al-Bashaireh et al. 2022). While high levels of potassium contamination have been reported in beads and bracelets made of natron glass these are surface effects attributed to working and annealing in hot ash and were observed when analysing unprepared surfaces by LA-ICP-MS (Rolland 2021: 41-43) and surface flakes by SEM-EDS (Davis and Freestone 2018: 117). The bracelets from Jordan have been analysed away from the surfaces in cross section by EPMA and are therefore considered to represent a compositional type distinct from typical southeastern Mediterranean natron glass.

### *4.1. Natron glass*

As has been widely discussed, the primary production of natron-based glass was mainly located in either Egypt or the Levant for most of the 1st millennium CE and the raw glass traded over long distances to secondary workshops where it was shaped into objects (Degryse 2014; Foy 2018; Freestone 2021). The centers of primary production shifted over time with each differentiated by relatively subtle changes in composition depending upon the local sand composition and recipe. Between the first and the fourth centuries, glass made in Egypt was decolourised using antimony and glass made in the Levant decolourised with manganese. From the fourth century, there was a change in production and antimony was no longer used as a decolouriser or an opacifier; Egyptian glassmakers began to manufacture an iron-rich glass containing manganese known as HIMT, while by the sixth century, Levantine glassmakers appear to have stopped decolourising their glass (reviewed with references by Freestone 2021). Egyptian glassmaking sands typically have a higher $TiO_2$ content (Foy et al. 2003) and glasses originating in Egypt are primarily distinguished from those of the Levant by their $TiO_2/Al_2O_3$ and $Al_2O_3/SiO_2$ ratios (Fig. 3; see Freestone et al. 2018, Schibille et al 2017).

In the present assemblage, the majority of glasses are of Levantine origin (Fig. 3). Four samples could be identified (Fig. 3) as individual examples of Egypt 2 (DHE 8) (8-9th centuries; Phelps et al. 2016; Schibille et al. 2019), Egypt 1a (DHL 20) (Late 600s – c. 720 CE: Schibille et al., op. cit.), Egypt 1b (DHL 37) (720-780 CE: Schibille et al. op. cit.) and Foy 2.1 (DHE 6) (6th cent CE: Foy et al. 2003, Cholakova et al. 2015).

One sample (a jar base, DHL 29, from a 6th -8th cent. AD context) in some ways resembles glass of Foy série 3.2, an Egyptian production dated to the fifth century AD (Foy et al.

2003, Cholakova and Rehren 2018), and, while a lack of manganese in this sample is not typical, the $Al_2O_3/SiO_2$ and $TiO_2/Al_2O_3$ ratios show a good correspondence (Fig.3), indicating a closely similar sand. This sample has only 14.7% $Na_2O$, as opposed to the range of 17-20% which is characteristic of Foy 3.2, according to the data collected by Balvanović and Šmit (2022). However, like MnO, the content of $Na_2O$ was determined by the practices of the glassmakers and our assessment of the similarity is based upon the characteristics of the sand and likely source of the glass.

Two samples of weakly coloured glass of Roman date (DHE 3 (3rd cent.) and DHE 9 (2nd -3rd cent. AD)) contain 0.6-0.8% $Sb_2O_5$ with MnO at background levels of 0.01-0.02%, indicating that they were decolorized by additions of antimony rather than manganese. In many respects they resemble typical Roman Sb-decolorized glass with low $Al_2O_3$ and $P_2O_5$, while their $TiO_2$ contents are also consistent with Roman-Sb. Their CaO contents, however, are slightly high at 7.02% and 7.06% respectively, whereas Roman-Sb glass typically has less than 6.0% CaO. The detection of c. 0.03% CuO in DHE3 (Table 1/2) may indicate that this sample includes recycled glass. If these glasses are recycled their low manganese contents suggest addition of a Levantine Roman glass with no added MnO. CaO contamination may also occur due to reaction with a limestone or lime-lined melting furnace (Chen et al 2021). Whatever the origins of this slight compositional anomaly the two samples appear to consist predominantly of Roman-Sb glass, believed on the basis of hafnium isotope evidence to have been produced in Egypt between the first and the fourth centuries AD (Barfod et al. 2020).

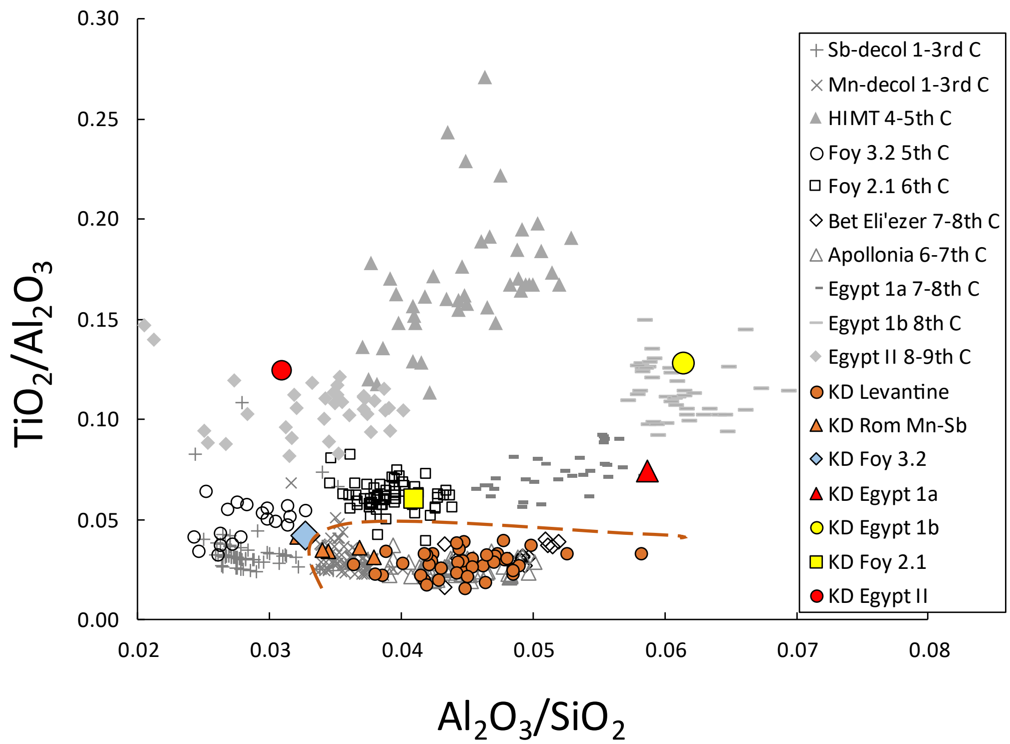


*Fig. 3. Compositions of the natron-based glasses from Khirbet adh-Dharih compared with major production groups of the 1st millennium CE. Reference fields from Foy et al. (2003), Silvestri (2008), Silvestri et al. (2008), Schibille et al. (2019), Freestone et al. (2015). Dashed line separates Egyptian from Levantine compositions. Note: Levantine glass groups are not distinguished.*

Levantine glass has low $TiO_2/Al_2O_3$ and a relatively narrow range of $Al_2O_3/SiO_2$ and lies along the base of Fig. 3. The individual Levantine productions show compositional overlap and are not as easily distinguished from one another as the Egyptian centers. The analyzed samples were primarily grouped on the basis of their $Na_2O/SiO_2$ and $CaO/Al_2O_3$ ratios (Fig. 4; cf. Al-Bashaireh et al. 2016a; Phelps et al. 2016). The low soda of the majority of raw glass analyzed from the primary production site at Bet Eli'ezer (Freestone et al. 2000), probably dated to the eighth century (see below) is distinctive and allows attribution of a group of eleven samples to this group (Fig. 4). Glass made at Apollonia has higher lime and intermediate soda and "Apollonia-type glass" is well represented (Fig. 4). However, three of the twenty-one samples assigned on this basis to Apollonia (DHE 1, 10 and DHL

21) have high MnO (>0.6%) which is not characteristic of Apollonia glass but of earlier production, for example at fourth century Jalame (Freestone 2020, Freestone et al. 2023). They may therefore represent Jalame glass or Apollonia glass recycled with earlier Levantine glass. These samples are therefore listed "Jalame/Apollonia" in Table 2, to reflect the uncertainty.

The standard manganese decolorized glass (Roman Mn) of the first to fourth centuries, possibly made in Sidon or Beirut (Freestone et al. 2023) is not easily distinguished from the fourth century production at Jalame (near Haifa) due to an overlap in $Na_2O$ and CaO contents (Fig.4). In the classic study of the Jalame glass by Brill (1988) $SiO_2$ was determined by difference, resulting in some uncertainty, but the recent study by Freestone et al. (2023) shows that Roman-Mn and Jalame glasses may be distinguished in terms of $Al_2O_3$ and $SiO_2$, although with some overlap (Fig. 5). Most of the earlier natron glass analyzed here (n=7) corresponds to Jalame production, although three samples (DHE 20, 24, 26) may be Roman Mn-decolorized glass and are labeled as such for illustrative purposes in Fig. 5.

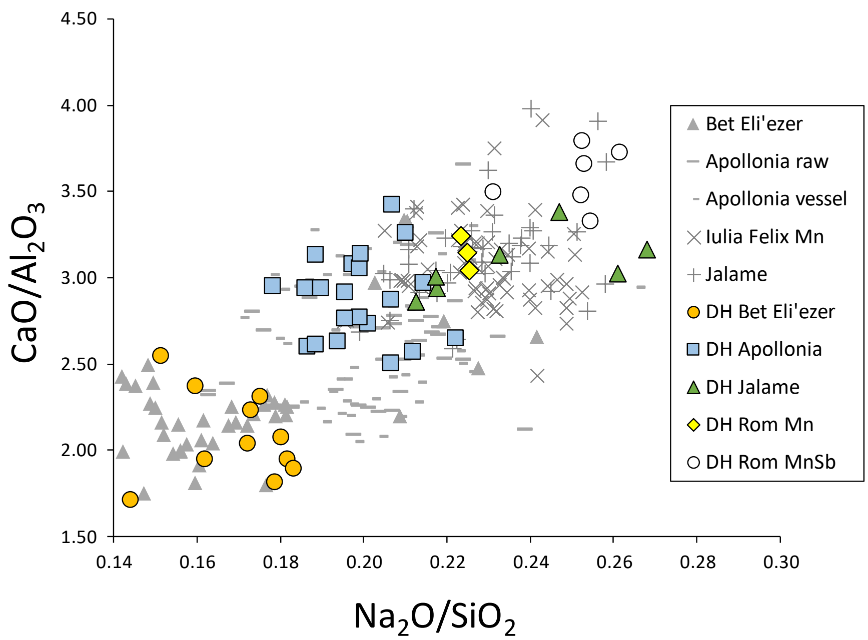


*Fig. 4. Compositions of the Levantine natron-based glasses from Khirbet adh-Dharih (DH) compared with major Levantine production groups of the 1st millennium CE. The samples are labelled according to their assignations in the present work, see the text for uncertainties. Reference data: Roman glass of 1-4th centuries represented by Jalame (Brill 1988), and the Iulia Felix wreck (Silvestri 2008, Silvestri et al. 2008); Apollonia raw glass from Freestone et al. (2000, 2008) and Tal et al. (2004); Apollonia-type vessel glass from Phelps et al. (2016); Bet Eli'ezer from Freestone et al. (2000 and unpublished).*

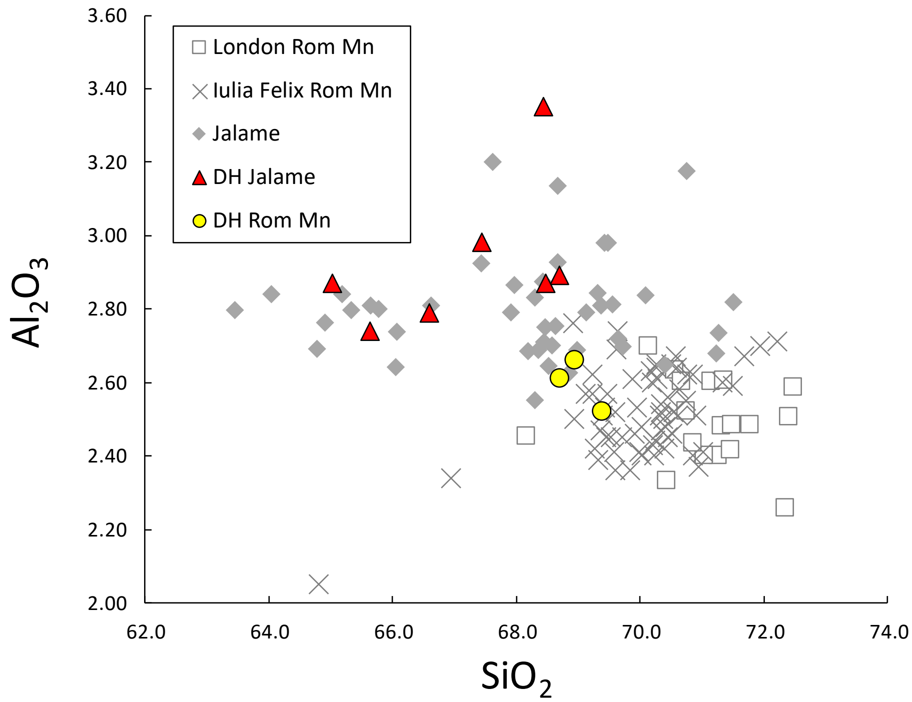


*Fig. 5. Potential Jalame or Roman-Mn glasses from Khirbet adh-Dharih compared with reference groups analyzed by EPMA from fourth century Jalame (Freestone et al. 2023) and typical Roman-Mn glass from the Iulia Felix wreck (Silvestri 2008, Silvestri et al. 2008) and Roman London (Freestone, unpublished). Most of the DH glass shown appears to correspond to Jalame production but several samples may be Roman-Mn and are labeled as such.*

A final group of natron glass contains in excess of 0.1% each of $Sb_2O_5$ and MnO and these represent mixtures of Roman-Mn and Roman-Sb glass, possibly including also some later glass types and reflect glass recycling (n=6: DHE 4, 5, 14, 21, 22, 27). It should be noted that several samples attributed to Jalame and Roman-Mn contain low amounts of $Sb_2O_5$ (n=3: DHE 26, DHL19, 26), reflecting glass recycling.

### *4.2. Plant ash glass*

The compositions of the seven analyzed samples of plant ash glass from Khirbet adh-Dharih are shown relative to Syrian/Eastern Mediterranean and Mesopotamian glass in Fig. 6, using the boundaries of Phelps (2018) and with typical regional glass types from el-Raqqa (Henderson et al. 2004), Tyre (Phelps 2018) and Sasanian glass from Veh Ardasir

(Mirti et al. 2008, 2009). Two of the samples (DHL 1, DHL 17) correspond to Mesopotamian type 2, while two (DHL 4, 18) are clearly eastern Mediterranean; as shown in Fig. 6, these resemble Group 1 glass from el-Raqqa, Syria (Henderson et al. 2004) but origins in Egypt or elsewhere in the Greater Syria region are possible as well. A cluster of three samples (DHL 6, 15, 16) appears to have been made using Eastern Mediterranean plant ash, as indicated by the MgO/CaO ratio, but have higher $Al_2O_3$ and these are characteristic of Tyre (Freestone 2002, Phelps 2018).

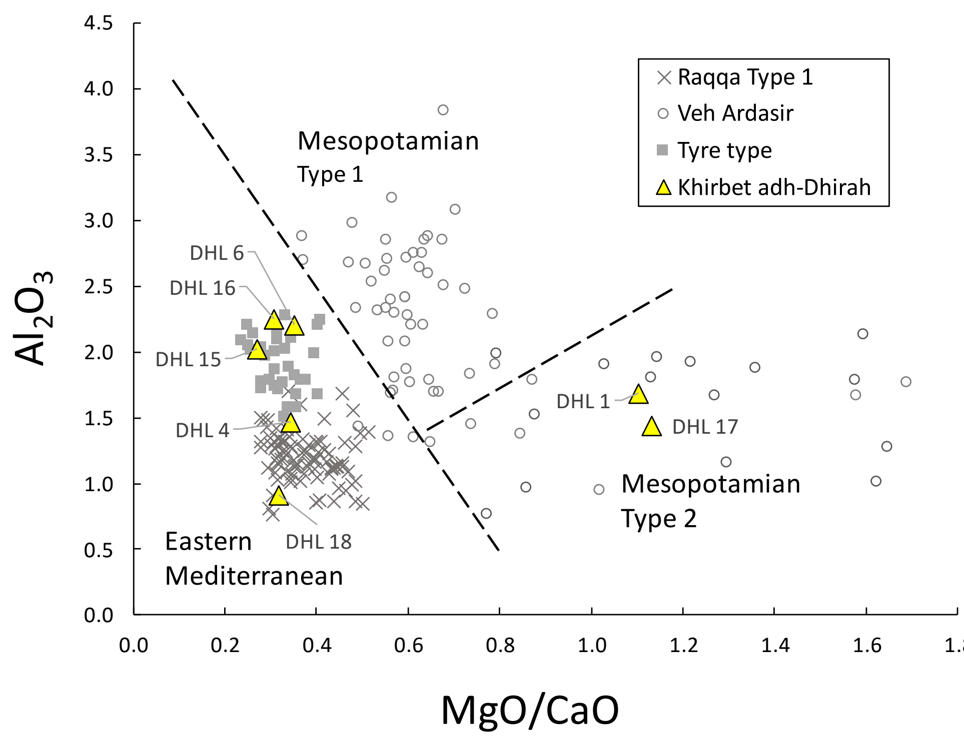


*Fig. 6. Plant ash glass from Khirbet adh-Dharih compared with plant-ash glass from el-Raqqa (Henderson et al., 2004), Tyre-type glass from Ramla (Phelps 2018) and Sasanian glass from Veh Ardasir (Mirti et al., 2008, 2009), using boundaries of Phelps (2018).*

## 5. Discussion

### *5.1. Recycling*

Evidence for glass recycling is present sporadically throughout the natron assemblage as decolorising components (Sb, Mn) or colourant components such as Cu and Pb (a component of opaque yellow and sometimes copper-coloured red or blue glasses) which are present in concentrations above the levels in glassmaking sand, but which are too low to have had a significant effect on the color of the glass (Table 2; Freestone 2015). This is particularly evident in the 1st to 4th cent. glass, where there is evidence of mixing of Sb-decolorized glass with other groups, as discussed above.

More subtle are the changes in base glass components due to contamination during re-melting episodes. In particular, $K_2O$ and $P_2O_5$ may increase due to contamination from the furnace atmosphere and fly ash (Paynter 2008, Rehren et al. 2010), CaO and MgO from fly ash, CaO and $Fe_2O_3$ from the walls of the melting chamber which was sometimes lined with a lime-rich layer (Chen et al. 2021), while Cl was lost due to volatilization (al-Bashaireh et al. 2016a; for a more detailed overview, see Barfod et al 2022). All these effects are particularly noticeable in the 6th -7th cent. Apollonia-type glass at Khirbet adh-Dharih but are hardly apparent in the later 8th cent. Bet Eli'ezer glass (Fig. 7). A less pronounced increase of MnO with $K_2O$ is also observed, consistent with increased intensity of recycling, but the mechanism causing the MnO increase is separate from that of the $K_2O$.

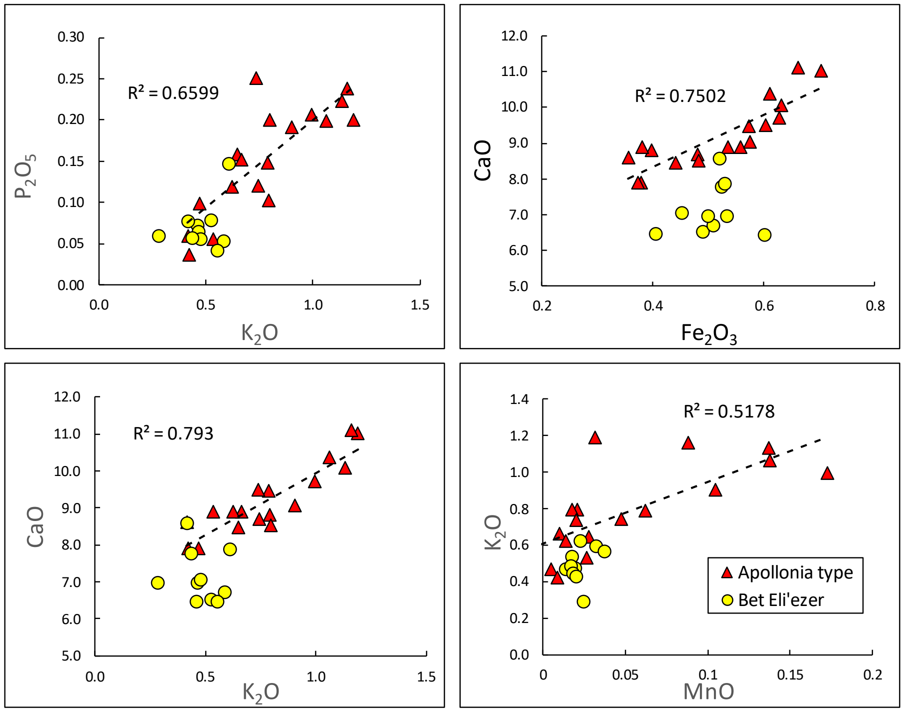


*Fig. 7. Correlations between selected oxides in 6-7th cent. Apollonia-type glass and 8th cent. Bet Eli'ezer glass. Trend lines and $R^2$ values are for Apollonia type.*

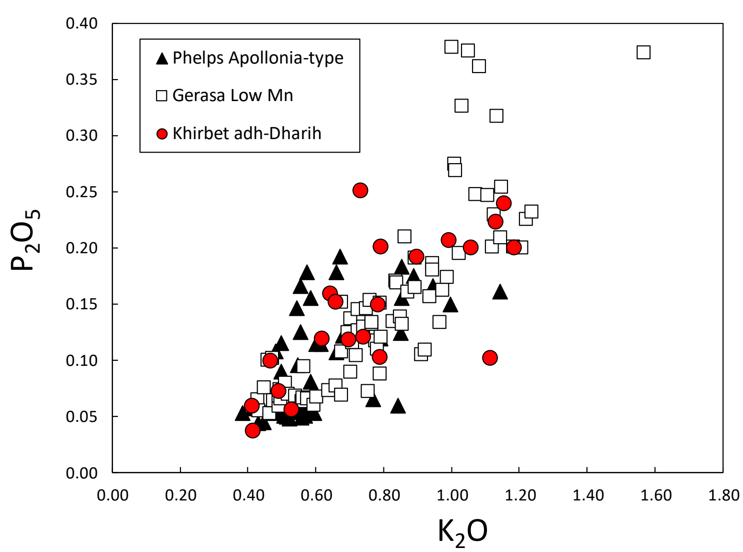


*Fig. 8. Apollonia-type glass from Khirbet adh-Dharih compared with Apollonia-type glass from cities west of the River Jordan (Phelps et al. 2016) and Jerash (Barfod et al 2022) in terms of recycling intensity, as indicated by potash and phosphorus oxide contamination.*

### *5.2. Chronological development*

The compositional analysis has allowed most of the sampled glass to be assigned to established groupings related to the source of the primary material. However, it needs to be understood that there are some uncertainties in the precise membership of the groups. For example, while the low $Na_2O/SiO_2$ Bet Eli'ezer grouping in Fig. 4 is reasonably secure, the analysis of raw glass from Bet Eli'ezer showed a small proportion of samples with high $Na_2O$, which corresponds more to Apollonia glass (Freestone et al. 2000). Therefore, some DH glass originating in Bet Eli'ezer may be hidden in our Apollonia group. We have also drawn attention to the overlap issue with respect to Jalame and Roman-Mn type glass; however, while it is not possible to be fully confident of the presence of Roman-Mn glass (Fig. 5) Jalame glass is very likely to be present in the assemblage. With respect to the plant ash group assignations, trace elements would clearly enable a more robust conclusion, but the present analysis is consistent with our general understanding of the archaeology of the region.

Group assignations are provided with the analytical data in Table 2, and a comparison of the compositional dating with that based upon archaeological context is provided in Supplementary Table S1. Agreement is generally good with few anomalies, probably due to intrusion of glass fragments into earlier deposits. On this basis it is possible to discuss the chronology of glass development at Khirbet adh-Dharih.

In some respects, the glass assemblage recorded here is similar to that of Gerasa (Jerash), located in the North part of Jordan (Barfod et al 2018, 2022), as well as to the contemporary glass recorded for the Byzantine and early Islamic periods from cities on the West side of the River Jordan, near the Mediterranean coast, such as Sepphoris, Jerusalem and Ramla by Phelps et al. (2016).

The glasses of the 1$^{st}$ to 4$^{th}$ centuries are represented by some tentatively assigned Roman Mn-decolorized glass originating from the Levant, a relatively small amount of Sb-decolorized Egyptian glass, with fairly common Mn-Sb compositions indicating mixing of these types. Whether the mixed glass arrived as pre-formed cullet, or as fresh glass which was recycled in Khirbet adh-Dharih or its hinterland, this is indicative of a significant supply of glass of Egyptian origin reaching the site and region.

Through the Byzantine periods, the evidence for glass originating outside the Levant declines, with fourth century material from Jalame, and most analyzed samples consistent with an origin in the furnaces of Apollonia, on the eastern Mediterranean coast and usually dated to the 6-7th centuries (Freestone 2020). The characteristic 4th cent. Roman glass, Egyptian HIMT, was not detected, while the significance of a single analysis of a jar (DHE 6) which could be interpreted as 6th cent. Foy (2003) Série 2.1 is uncertain, as the vessel is from a 4th century context. Evidence for the use and intensive recycling of Apollonia glass at DH is clear in this period, consistent with the findings from the Decapolis cities of Gerasa, Capitolias and Gadara and the archaeological sites of Umm el-Jimal and Al-Fudein (Barfod et al 2022, El-Khouri 2014, Abd-Allah 2010, Al-Bashaireh et al. 2016a, Al-Bashaireh et al. 2016b, Al-Bashaireh 2016). Following the arguments of Barfod et al (2022) on recycling intensity, it can be seen in Fig. 7 that the Khirbet adh-Dharih Apollonia-type glass assemblage has potash and phosphorus oxide ranges comparable to above mentioned sites, but they extend to higher concentrations than those in the glass from consumption sites in the coastal plain, confirming that there was more dependence upon recycling East of the Jordan valley, where fresh glass from Apollonia would have been less accessible.

From the early Islamic period, Khirbet adh-Dharih has yielded a significant amount of natron glass likely to have originated in the Bet Eli'ezer furnaces (near Hadera), confirming the findings from Umm el-Jimal in the North (Al-Bashaireh et al. 2016a). Schibille (2022: 90) has observed that Bet Eli'ezer glass is "surprisingly rare" even in the Levant, so its appearance here is therefore a significant occurrence. Glass from Bet Eli'ezer was not found at Jerash (Barfod et al 2022), which suffered a devastating earthquake in 750 AD, and this may suggest that glassmaking there began in the mid-late 8th cent., and was short lived. The typological evidence from elsewhere, however, is not fully consistent with this view, suggesting that some Bet Eli'ezer material was present in the first half of the eighth century (Phelps et al. 2016, Phelps 2018). Given the likely uncertainties due to sampling strategy, archaeological context and assignment to compositional groups, as well as the inferred short duration of Bet Eli'ezer production, the discrepancies are not large. The evidence for recycling of Bet Eli'ezer type glass is far less apparent than for the Apollonia type, which may be readily explained if the duration of its production was limited. While Apollonia glass may have been in circulation for well over a century, Bet Eli'ezer production may have continued no more than few decades, so that the number of recycling episodes would have been more limited. Furthermore, Bet Eli'ezer glass may have been recycled into the much larger reservoir of pre-existing Apollonia glass, where its signature would be hard to distinguish.

Through the late Byzantine and early Islamic periods, limited amounts of Egyptian natron glass are apparent, in the form of Foy 2.1 in the 6$^{th}$ century and Egypt I and II in the eighth-ninth centuries. Overall, these compositions have been recorded more frequently in the analyzed assemblage at Jerash, but this may be due to the special circumstances of preservation there (Barfod et al 2022). As well as the findings from Jerash, the continued importation of Egyptian glass into the Levant through the eighth and possibly the ninth centuries is also consistent with work in the coastal plain (Freestone et al. 2015, Phelps et al 2016) and from a shipwreck south of Haifa (Benzonelli et al. 2024). Plant ash glass appears in the region around the end of the eighth century (Phelps et al. 2016, Phelps 2018) and is represented at DH by two samples from Mesopotamia as well as several samples made of glass produced in Tyre which seems to become active as a continuation of Levantine coastal glass production in the ninth century. Plant ash glass from unspecified production centers in the eastern Mediterranean is also present. Finally, two bangles have potash-rich mineral soda compositions and correspond to similar glass found in bangles from Dohaleh (north Jordan) (Al-Bashaireh et al. 2022), from Umm el-Jimal (East Jordan) (Al-Bashaireh 2016), and Tell Abu Sarbut and Khirbat Faris in central Jordan (Boulonge and Henderson 2009); it has been tentatively suggested that this compositional type has an Anatolian origin (Al-Bashaireh et al. 2022).

**6. Conclusions**

The electron microprobe analysis of glass from Khirbet adh-Dharih has provided a compositional sequence from the Roman through to the Abbasid periods and suggests that glass originating from beyond the Levant was more commonly obtained in the Roman and early Islamic periods. Evidence for recycling is particularly apparent in the Byzantine Apollonia-type glass. These findings extend the pattern previously observed at sites in the northern region of Jordan into its southern region. The occurrence of glass from the Bet Eli'ezer furnaces in significant quantities is consistent with the view that this material may have been more widespread than has been thought, but that its production was short-lived, perhaps occurring in the latter part of the 8$^{th}$ cent.. It appears that the Byzantine period was particularly dependent upon glass from Apollonia, which was intensively recycled, whereas glass from Egypt and Mesopotamia becomes more available in the early Islamic period.

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## References

Abd-Allah, R. (2010). Chemical characterisation and manufacturing technology of late Roman to early Byzantine glass from Beit Ras/Capitolias, Northern Jordan. *Journal of Archaeological science*, *37*(8), 1866-1874.

Al-Bashaireh, K. (2016). Production technology of glass bracelets from the west cemetery of Umm el-Jimal in northeastern Jordan. Mediterranean Archaeology and Archaeometry, 16(3), 17-17.

Al-Bashaireh, K., Al-Mustafa, S., Freestone, I. C., & Al-Housan, A. Q. (2016a). Composition of Byzantine glasses from Umm el-Jimal, northeast Jordan: Insights into glass origins and recycling. *Journal of Cultural Heritage*, *21*, 809-818.

Al-Bashaireh, K., Alama, E., & Al-Housan, A. Q. (2016b). Analytical and technological study of Roman, Byzantine and early Islamic (Umayyad) glasses from Al-Fudein archaeological site, Jordan. *Mediterranean Archaeology and Archaeometry*, *16*(1), 257-268.

Al-Bashaireh, K., Freestone, I. C., & Gregory, T. (2022). Composition of glass bracelets and rings from the Ayyubid-Mamluk cemetery at Dohaleh, north Jordan. Journal of Archaeological Science: Reports, 46, 103689.

Al-Muheisen, Z., & Villeneuve, F. (1988). Fouilles & Khirbat edh-Dharih (Jordanie). Un village, son sanctuaire et sa nécropole aux époques nabatéenne et romaine (Ier-

[Véme siécles ap. J-C.). Comptes rendus de l'Académie des Inscriptions et Belles Lettres: 458-479, Paris.

Al-Muheisen, Z., & Villeneuve, F. (2005). Archaeological research at Khirbat adh-Dharih. ADAJ, 49, 489-499.

Al Muheissen, Z. & Villeneuve, F. (2013). The Caravan Routes. Dharih. In Ababsa, M. (Ed.), *Atlas of Jordan: History, Territories and Society* (Vol. 32). Publications de l'Institut français du Proche-Orient, Amman.Pp. 151-154.

Balvanović, R.V. and Šmit, Ž., (2022). Emerging glass industry patterns in late antiquity Balkans and beyond: new analytical findings on Foy 3.2 and Foy 2.1 glass types. *Materials*, *15*(3), p.1086.

Barfod G.H., Freestone I.C., Lichtenberger A., Raja R., Schwarzer H. (2018) Geochemistry of Byzantine and Early Islamic glass from Jerash, Jordan: Typology, recycling, and provenance. *Geoarchaeology* 33:623–640.

Barfod, G.H., Freestone, I.C., Lesher, C.E., Lichtenberger A. and Raja R. (2020). 'Alexandrian' glass confirmed by hafnium isotopes. *Sci Rep* **10,** 11322. https://doi.org/10.1038/s41598-020-68089-w

Barfod, G.H., Freestone, I.C., Jackson-Tal, R.E., Lichtenberger, A., & Raja, R. (2022). Exotic glass types and the intensity of recycling in the northwest Quarter of Gerasa (Jerash, Jordan). *Journal of Archaeological Science*, *140*, p.105546.

Benzonelli, A., Natan, E., Gorin-Rosen, Y., & Freestone, I. C. (2024). Composition and affinities of glass from the Ma'agan Mikhael B shipwreck,Israel.*Archaeometry* 66, 340-351. https://doi.org/10.1111/arcm.12929

Boulogne, S., & Henderson, J. (2009). Indian Glass in the Middle east? Medieval and Ottoman Glass Bangles from central Jordan. Journal of Glass Studies, 53-75.

Brill, R.H. (1970). The chemical interpretation of the texts. In A.L. Oppenheim, R.H. Brill, D. Barag and A. von Saldern *Glass and Glassmaking in Ancient Mesopotamia*. New York, Corning Museum of Glass. Pp. 105-128.

Brill, R. H. (1988). Scientific investigations of the Jalame glass and related finds. In *Excavations at Jalame: site of a glass factory in late Roman Palestine* (pp. 257-294).

Brill, R. H. (1999). Chemical analyses of early glasses, The Corning Museum of Glass. *Corning, New York*.

Chen, C., Freestone, I. C., Gorin-Rosen, Y., & Quinn, P. S. (2021). A glass workshop in 'Aqir, Israel and a new type of compositional contamination. *Journal of Archaeological Science: Reports*, *35*, 102786.

Cholakova, A., & Rehren, T. (2018). A late antique manganese decolourised glass composition: interpreting patterns and mechanisms of distribution. *Things that Travelled: Mediterranean Glass in the First Millennium AD. UCL Press, London*, 46-71.

Cholakova, A., Rehren, T., & Freestone, I. C. (2016). Compositional identification of 6th c. AD glass from the Lower Danube. *Journal of Archaeological Science: Reports*, *7*, 625-632.

Davis, M., & Freestone, I. C. (2018). Trading North: Glass-working beyond the edge of the empire. In: Rosenow D., Phelps M., Meek A. and Freestone I. C. (eds), Things that travelled: Glass in the First Millennium CE. London: UCL Press, pp. 107-133.

Dussart, O. (2007). Fouilles de Khirbet edh-Dharih, III-Les verres. Syria. Archéologie, art et histoire, (84), 205-247.

El-Khouri, L. (2014). Glass production in the early Byzantine period (4th–7th century) at Gadara (umm Qais), Jordan, area W, 2011 season of excavation. *Levant*, *46*(1), 89-97.

Foy D, Picon M, Vichy M, Thirion-Merle V (2003) Caractérisation des verres de la fin de l'Antiquité en Méditerranée occidentale: l'émergence de nouveaux courants commerciaux. In: Foy D, Nenna M-D (eds) Échanges et commerce du verre dans le monde antique : actes du colloque de l'Association française pour l'archéologie du verre, Aix-en-Provence et Marseille, 7-9 juin 2001. Éditions Monique Mergoil, Montagnac, pp 41–85.

Foy, D. (2018). An overview of the circulation of glass in antiquity. In Wilson, A. and Bowman, A.K. eds., 2018. *Trade, commerce, and the state in the Roman world*. Oxford University Press. pp.265-299.

Freestone, I. C. (2015). The recycling and reuse of Roman glass: analytical approaches. *Journal of glass studies* (57): 29-40.

Freestone, I. (2020). Apollonia Glass and Its Markets: An Analytical Perspective. In Tal, O.(Ed). *Apollonia-Arsuf. Final report of the excavations, Volume II. Excavations outside the Medieval town walls*. University Park, Pennsylvania, Eisenbrauns. pp. 341-348.

Freestone, I. C. (2021). Glass Production in the First Millennium CE: A Compositional Perspective. In F. Klimscha, H. J. Karlsen, S. Hansen, & J. Renn (Eds.), *Vom Künstlichen Stein zum durchsichtigen Massenprodukt / From artificial stone to translucent mass-product*. Berlin Studies of the Ancient World 67, Edition TOPOI. pp. 245-263

Freestone, I. C., Gorin-Rosen, Y., & Hughes, M. J. (2000). Primary glass from Israel and the production of glass in late antiquity and the Early Islamic period. In: Nenna M-D (ed) *La route du verre. Ateliers primaires et secondaires du second millénaire av. J.C. au Moyen Âge*. Maison de l'Orient Méditerranéen-Jean Pouilloux, Lyon. pp 65–83.

Freestone, I. C., Jackson-Tal, R. E., Taxel, I., & Tal, O. (2015). Glass production at an early Islamic workshop in Tel Aviv. *Journal of Archaeological Science*, *62*, 45-54.

Freestone I.C., Degryse, P., Lankton J., Gratuze B. and Schneider J. (2018) HIMT, glass composition and commodity branding in the primary glass industry. In Rosenow D., Phelps M., Meek A. and Freestone I. C. (eds) *Things That Travelled: Glass in the First Millennium CE*. London: UCL Press, 159-190.

Freestone I.C. , Barfod G H., Chen C., Larson K.A., & Gorin-Rosen Y. (2023). Glass production at Jalame, Israel: Process, composition and relationship to Roman glass in Europe. *Journal of Archaeological Science: Reports,* Volume 51, 104179, https://doi.org/10.1016/j.jasrep.2023.104179.

Gorin-Rosen, Y., & Katsnelson N. (2007). Local Glass Production in the Late Roman–Early Byzantine Periods in Light of the Glass Finds from Khirbat El-Ni‘Ana. *‘Atiqot* 57, 37-154.

Henderson, J., McLoughlin, S. D., & McPhail, D. S. (2004). Radical changes in Islamic glass technology: evidence for conservatism and experimentation with new glass recipes from early and middle Islamic Raqqa, Syria. *Archaeometry*, *46*(3), 439-468.

Lilyquist, C., Brill, R.H. and Wypyski, M.T. (1993). *Studies in early Egyptian glass*. New York: Metropolitan Museum of Art.

Mirti, P., Pace, M., Negro Ponzi, M. M., & Aceto, M. (2008). ICP–MS Analysis of Glass Fragments of Parthian and Sasanian Epoch from Seleucia and Veh Ardaš? R (Central Iraq). *Archaeometry*, *50*(3), 429-450.

Mirti, P., Pace, M., Malandrino, M., & Ponzi, M. N. (2009). Sasanian glass from Veh Ardašīr: new evidences by ICP-MS analysis. *Journal of Archaeological Science*, *36*(4), 1061-1069.

Paynter, S. (2008). Experiments in the reconstruction of Roman wood-fired glassworking furnaces: waste products and their formation processes. *Journal of Glass Studies*, (50), 271-290.

Phelps, M. (2018). Glass supply and trade in early Islamic Ramla: an investigation of the plant ash glass. In Rosenow, D., Meek, A., Phelps, M. and Freestone, I.(eds) *Things that travelled: Mediterranean glass in the first millennium CE*, UCL Press. pp.236-282.

Phelps, M., Freestone, I. C., Gorin-Rosen, Y., & Gratuze, B. (2016). Natron glass production and supply in the late antique and early medieval Near East: The effect of the Byzantine-Islamic transition. *Journal of Archaeological Science*, *75*, 57-71.

Rehren, T., Marii, F., Schibille, N., Stanford, L., & Swan, C. (2010). Glass supply and circulation in Early Byzantine Southern Jordan. In: Drauscke J, Keller D (eds*), Glass in Byzantium—production, usage, analyses.* RGZM, Mainz, 65–82.

Rolland, J. (2021). *Le verre de l'Europe celtique, Approches archéométriques, technologiques et sociales d'un artisanat du prestige au second âge du Fer*. Sidestone Press.

Sartori, N. (2015). Le bain tardif de Dharih (Jordanie méridionale). *Syria. Archéologie, art et histoire*, (92), 123-131.

Schibille, N. (2022). *Islamic glass in the making: chronological and geographical dimensions*. Leuven University Press.

Schibille, N., Sterrett-Krause, A. and Freestone, I.C. (2017) Glass groups, glass supply and recycling in late Roman Carthage. *Archaeological and Anthropological Sciences*, *9*, pp.1223-1241.

Schibille, N., Gratuze, B., Ollivier, E., & Blondeau, É. (2019). Chronology of early Islamic glass compositions from Egypt. *Journal of Archaeological Science*, *104*, 10-18.

Silvestri, A. (2008). The coloured glass of Iulia Felix. *Journal of archaeological science*, *35*(6), 1489-1501.

Silvestri, A., Molin, G., & Salviulo, G. (2008). The colourless glass of Iulia Felix. *Journal of archaeological science*, *35*(2), 331-341.

Tal, O., Jackson-Tal, R.E., & Freestone, I.C. (2004). New evidence of the production of raw glass at late Byzantine Apollonia-Arsuf, Israel. *Journal of Glass Studies*,46, 51-66.

Tal, O., Jackson-Tal, R. E., & Freestone, I. C. (2008). Glass from a Late Byzantine secondary workshop at Ramla (south), Israel. *Journal of Glass Studies*, 81-95.

Vicenzi, E. P., Eggins, S., Logan, A., & Wysoczanski, R. (2002). Microbeam characterization of corning archeological reference glasses: new additions to the smithsonian microbeam standard collection. *Journal of Research of the National Institute of Standards and technology*, *107*(6), 719.

Villeneuve, F., & Al Muheissen, Z. (2008). Le sanctuaire nabatéo-romain de Dharih (Jordanie): nouvelles découvertes, 2001-2008. *Comptes rendus des séances de l'Académie des inscriptions et belles-lettres*, *152*(4), 1495-1520.

Villeneuve, F.,(2011). *Dharih (Jordanie méridionale): village chrétien puis musulman (vi$^{e}$-ix$^{e}$ siècles) dans les ruines d'un sanctuaire nabatéen*. In: Borrut A., Debie M., Papaconstantinou A., Pieri D., and Sodini J.-P. (Eds), Le Proche-Orient de Justinien aux Abbassides: Peuplement et dynamiques spatiales. Actes du colloque «Continuités de l'occupation entre les périodes byzantine et abbasside au Proche-Orient, VIIe-IXe siècles". Paris, p. 315-330.

Wagner, B., Nowak, A., Bulska, E., Hametner, K., & Günther, D. (2012). Critical assessment of the elemental composition of Corning archeological reference glasses by LA-ICP-MS. *Analytical and bioanalytical chemistry*, *402*(4), 1667-1677.

Waliszewski, T. (2001). Céramique Byzantine et proto-Islamique de Khirbet EdhDharih (Jordanie Du Sud). In E. Villeneuve and P. Watson (Eds), La céramique byzantine et proto-islamique en Syrie-Jordanie (IVe–VIIIe Sièles Apr. J.-C.). Beruit: Institut français d'archaéologie du Proche-Orient. Pp. 95–106.