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Natron glass production and supply in the late antique and early medieval Near East: The effect of the Byzantine-Islamic transition

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ABSTRACT

Palestine and Egypt supplied the Mediterranean and Europe with virtually all of its glass for most of the first millennium CE. While the Muslim conquest in the 7th century saw major political and economic adjustment, immediate changes to material culture appear to have been minimal. This paper examines the impact of the Byzantine-Islamic transition on the natron glass industry of Palestine from the 7th to 12th century. A series of 133 well-contextualised glass vessels from selected excavations in modern day Israel have been analysed for major, minor and trace elements using LA-ICP-MS. These glasses are assigned to previously established primary production groups, allowing the elucidation of the chronology of key changes in glass production in the region. Results indicate a relatively abrupt compositional change in the late 7th - early 8th centuries, covering the reforming reigns of al-Malik and al-Walid, which marks the end of "Byzantine" glass production and the establishment of the furnaces at Bet Eli'ezer. At about this time there was an influx of glass of an Egyptian composition. Production of Bet Eli'ezer type glass appears to have been limited to a short time span, less than 50 years, after which natron glass production in Palestine ceased. Plant ash glass is first encountered in the late 8th-early 9th century, probably as a result of reduced local natron glass production creating the conditions in which plant ash glass technology was adopted. Egypt continued to produce natron glass for up to a century after its demise in Palestine. It is reasoned that the change and then collapse in natron glass production in Palestine may well have been as a consequence of a reduction in the quantities of available natron. This affected Palestine first, and Egypt up to 100 years later, which suggests that the factors causing the reduction in natron supply originated at the source and were long term and gradual, not short term events.

1. Introduction

The centuries following the Arab conquests in the Near East represent a period of great political, economic and social change, and how these changes are reflected in the archaeological record is an area of major interest. Glass is a category of material culture which exhibits significant change in composition around this time and which might be expected to yield important information on the broader developments that occurred.

It is widely recognised that glass production conformed to a centralised production model during the Roman and Byzantine periods (Nenna et al., 1997; Freestone et al., 2000; Degryse, 2014). Large tank furnaces in Egypt (e.g. Nenna, 2015) and Palestine (Gorin-Rosen, 2000; Tal et al., 2004), melted many tonnes of sand and natron into large slabs which were broken into chunks and distributed to a large dispersed network of secondary vessel fabrication workshops across the Empire and beyond.

While the general form of the glass industry in the first millennium CE is now understood, key issues remain to be resolved. These include, in particular, the nature and timing of technological change to plant ash glass, the changing distribution of primary production sites and the supply of glass between different regions of the eastern Mediterranean, and how these changes relate to wider social, economic and political developments of the time. An improved compositional and chronological resolution of glass compositional groups will ultimately facilitate a much increased

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understanding of the trade in glass across the ancient and early medieval worlds (Rehren and Freestone, 2015).

The present paper addresses key outstanding questions related to the chronology and characterisation of glass production groups evident during the Byzantine-Islamic transition (7–9th centuries). The aim is to develop a framework within which the major technological change from the use of mineral soda (natron) to soda-rich plant ash as a flux (Sayre and Smith, 1974; Gratuze and Barrandon, 1990; Shortland et al., 2006) may be better understood. Current understanding of the chronology of this change and its precursors is imprecise. In the core production area of Palestine, our information is based mainly on the analysis of material from primary production sites, which due to the absence of diagnostic material culture, can often be difficult to date. Furthermore, because the material analysed has been abandoned rather than utilised to make vessels, it is not clear that it is fully representative. These issues are addressed below by the analysis of glass vessels from well-defined archaeological contexts and, where possible, of diagnostic forms.

This paper presents major and trace element compositions of over one hundred well-dated glass vessels of natron-type glass from excavated consumer sites in Israel. The much improved chronological resolution, coupled with an analytical technique with high accuracy and sensitivity, has resulted in a significantly improved understanding of both the chronologies and compositions of the principal chemical groups. This has enabled us to track changes in group dominance and technology, improving our understanding of the relationship between Palestinian and Egyptian glass production, and providing greater understanding as to when and why plant ash glass appeared in the Levant. These changes are discussed within the wider economic, political and cultural developments of the period.

2. Materials and methods

2.1. Sites and samples

The results of the analysis of 133 natron glass vessels from ten sites in Israel are presented here. Plant ash glasses were also identified but will be the subject of detailed consideration in a separate paper which will identify the types and provenance, and discuss the potential origins of and the mechanisms in which plant ash glass technology came to be used in Palestine (Phelps Forthcoming).

The analysed vessels cover the Late Byzantine/Early Umayyad to Fatimid periods (7th to 12th century). They are from controlled excavations undertaken by the Israel Antiquities Authority (IAA) from 17 excavations at ten sites, selected to provide a wide geographical spread and range of settlement types. The samples were chosen from mainly diagnostic fragments of common, domestic vessel types – bottles, bowls, goblets, beakers – with unique and rare forms avoided where possible. Some decorated forms – e.g. trailed, mould blown, pinched and tonged types – and coloured types were included, such as cobalt blue and manganese decoloured types, but other intentionally coloured glass (e.g. copper and lead) were excluded. Dating was paramount in sample selection, and relied upon a combination of context (stratigraphy, pottery and coinage), vessel form and fabric (colour, fabric quality). Typological dating using glass is relatively advanced in Israel (Gorin-Rosen, 2010a). A sample catalogue with context details, colour, dating, form and decoration can be found in Appendix C (supplementary material).

The vessels derive from three types of site, they can be categorised as: urban centres, military sites and rural settlements (Fig. 1). The urban centres include excavated locations in Bet Shean, Caesarea, Jerusalem, Ramla, Sepphoris and Tiberias. Ramla was unique in Palestine, being the only settlement to have been newly founded post-conquest (c. 715) as a Muslim city. It was to become very prosperous due to its administrative role and important trading position. The others cities were ancient and, on the whole, continued to have economic prosperity post-conquest (see Avni, 2014; Petersen, 2005), although Bet Shean and Caesarea declined in size due to their loss of administrative roles to Tiberias and Ramla, which took over as regional capitals of Jund al-Urdunn and Filastin respectively. Caesarea also lost links to Mediterranean trade networks. Ashdod Yam and Ha-Bonim were military installations dating from the late 7th century forming part of a Ribat system of 20 forts along the Palestine coast (Vunsh et al., 2013; Khalilieh, 1999). The rural sites comprise Ahihud, a small settlement east of Akko (Acre) in the north, and Nahal Shoval and Tel Rosh in the south of the country. The latter two were small settlements within a prosperous agricultural region in the northern Negev Desert near Beersheba. Site details are shown in Table 1. Note that a site License (or Permit) for each excavation is listed, this is the number provided to excavations by the IAA and is useful for linking this work to the published reports, particularly as some locations have more than one excavation.

2.2. Analytical methods

Analysis was by LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) on small detached glass fragments at the Ernest-Babelon laboratory, IRAMAT, Orleans, France. Elements were quantified using a Thermo Fisher Scientific Element XR mass spectrometer equipped with a three stage detector utilising a dual mode (counting and analog) secondary electron multiplier (SEM) giving a linear dynamic range over nine orders of magnitude associated with a single Faraday collector. This increases the linear dynamic range by three orders of magnitude, which is particularly important as the dilution of samples is impossible with laser ablation in contrast to solution ICP-MS, and therefore allows the analysis of major, minor, and trace elements in a single run regardless of their concentrations and their isotopic abundance. Analysis was performed over two campaigns. Campaign 1 (samples from Ahihud, Sepphoris and Bet Shean) used a VG UV-laser, generated by a Nd YAG pulsed beam and operating at 266 nm wavelength, 3–4 mJ power and 7 Hz frequency. An argon stream (1.15–1.35 l/min) carried the ablated material to the plasma torch. Campaign 2 (the remaining sites) used a Resonetics RESOlution M50e ablation device. This is an excimer laser produced by argon fluoride at 193 nm wavelength, and operated at 4 mJ and 7 Hz. It is a dual gas system with helium (0.6 l/min) released at the base of the chamber, which carried material to an argon stream (1.2 l/min). For both campaigns ablation time was set to 70 s: 20s pre-ablation to reduce potential contamination and 50s collection time. Fresh fractures were analysed where possible to further avoid contamination or corrosion. Blanks were run between samples. Spot sizes were set to 100 μm (although reduced to 70 μm when saturation occurred). For campaign 1, two areas were analysed per specimen to investigate possible heterogeneity in the samples. The agreement between the sites were found to be consistently good, so for Campaign 2 only one spot was analysed per sample. During analysis live counts were observed so that element spikes signifying the presence of inclusions or other compositional heterogeneities could be identified. When this occurred the results were discarded and a new site selected.

Calibration was performed using five reference standards – NIST610, Corning B, C and D, and APL1 (an in-house standard glass with composition determined by Fast Neutron Activation Analysis which is used for chlorine quantification) – which were run periodically to correct for drift. The standards were used to calculate the

Fig. 1. Map of Israel showing sites mentioned in the text. Red dots are sample sites and white diamonds are primary production sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

response coefficient (k) of each element (Gratuze, 1999, 873). The calculated values were normalised against ^{29}Si, the internal standard, to produce a final percentage. Corning A and NIST612 were analysed independently of calibration to provide comparative data. A total of 58 elements were recorded.

Accuracy and precision data for analysed and known values of Corning A (Brill, 1999; Wagner et al., 2012; Vicenzi et al., 2002) and NIST612 (Pearce et al., 1997) are presented in Appendix D (supplementary material). For the major elements the analysed values were within 5% relative for all elements, with the exception of alumina (7%; campaign 1) and lime (13%; campaign 2). However, comparative analysis of samples by EPMA gave a mean relative difference between the techniques of 3.67% for Al_2O_3 in campaign 1 and of 2.42% for CaO in campaign 2. In view of the close correspondence between EPMA and LA-ICP-MS and for consistency, we have used only the laser ablation results in the present study. For most trace elements ICP-MS was within 10% and all, except Ag, Ta_2O_3, Eu_2O_3, P_2O_5, and Cl, within 20% of the known values. Coefficients of variation for all major elements were <5%, and most <2%. For the minor and trace elements, most were <5% and all <10%, with the exception of Eu_2O_3 (campaign 1). Chromium oxide data is omitted for some samples, this is due to a contaminated argon cylinder during the early stages of campaign 2, later samples were unaffected.

Multivariate statistical analysis performed in R (Version 3.1.2) was used in the interrogation of the data. The compositional groups were identified using hierarchical cluster analysis (HCA) using Ward's method. This method measures similarity using the error sum of the squares with the distance between points represented by squared Euclidian distance (see Shennan, 1997, 741; Baxter, 2003, 92-3). Data was input as standardised variables. The results were displayed using principal component analysis (PCA). Components with eigenvalues above 1 were used (Shennan, 1997, 290), with preference for those principal components (PC) describing the most variation.

3. Results

3.1. Compositional groups

The results present the dataset of 133 natron glasses. Individual sample results with selected oxides are shown in Appendix A and

Table 1
Sample site information.

Location	Site	License	N	Date range	Excavation report	Glass report
Ahihud	Moshav Ahihud	A-3747	13	8th	Porat and Getzov 2010	Gorin-Rosen in Porat and Getzov 2010
Ashdod-Yam	Ashdod-Yam Castle	A-2844; A-2989; A-2658	5	8-11th	Raphael 2014	Ouahnouna 2014
Bet Shean	Youth Hostel	A-2885	1	10-11th	Sion 2000; Sion 2014	Katsnelson 2014
Caesarea	South Western Zone	Insula W2S3	3	7-10th		Winter, T in Prep
Ha-Bonim	Ha-Bonim Castle	A-3032	23	8-11th	Barbé et al., 2002	Gorin-Rosen, Y in Prep
Jerusalem	City of David: Giv'ati car park	A-3835	5	7-9th	Shukron and Reich 2005	Winter, T in Prep
	The Old City: Wilson's Arch and Great Causeway	A-5125; A-5570	30	7-9th	Onn et al., 2011	Katsnelson 2016
Nahal Shoval	Nahal Shoval	A-6362	9	8-10th	Daniel 2005	Winter, T in Prep
Ramla		A-3592	2	7-11th		Gorin-Rosen, Y in Prep
	Ma'asiyaha Junction	A-4740	7	late 8th-11th	Haddad 2013	Gorin-Rosen 2013
	Lod-Na'an railroad track	A-4768	4	8-10th	Haddad 2010	Gorin-Rosen 2010b
	Ha-Nevi'im Nursery School	A-5947	24	early 8th	Haddad 2011	Gorin-Rosen 2011
	Ha-Etzel Street	A-6297	2	late 8th-10th	Toueg 2013	Winter 2013
	Ha-Hez Street	A-6490	5	early 8th-early 11th	Toueg and Torgë 2015	Winter 2015
Sepphoris	Moshav Zippori	A-3791; A-3821	12	7th	Tepper 2010	Gorin-Rosen 2010c
Tel Rosh		A-6055	3	7-9th		Winter, T in Prep
Tiberias	Roman Theatre	A-5583	6	7-9th	Atrash 2010	Gorin-Rosen, Y in Prep

the full data set is presented in the supplementary material. The criterion used to separate natron glass from plant ash glass was contents of MgO and K_2O below 1.5% (Lilyquist et al., 1993). There was a single exception, RAM 5947-20, with typically low K_2O but enriched in MgO at 1.7%. Elevated levels of magnesia have also been observed in tank furnaces producing natron glass at Apollonia (Tal et al., 2004) and also in vessels from Carthage (Schibille et al., 2016). These vessels have been attributed to a high Mg sub-group of Levantine I glass, and so this sample was permitted as a natron glass (Schibille et al., 2016).

Oxide selection is crucial in producing meaningful results from HCA. Eight oxides were chosen representing geological factors, i.e. the mineralogical make-up of the sands (Al_2O_3, CaO, SrO, Fe_2O_3, TiO_2, ZrO_2) and anthropogenic factors, i.e. recipe (Na_2O, SiO_2), this is the mix of natron to sand. Other trace elements, such as the REE, were not used as they tend to be more regionally defined and less able to pick out differences between geologically close sand deposits (Degryse and Shortland, 2009, 141; see results below). Five samples were also removed (see caption Fig. 2); these were intermediate or outlier samples which did not fall into the main identified groups and will not be discussed further.

Hierarchical cluster analysis split the data into two main branches, which could be further sub-divided to create four groups; N-1, N-2, N-3 and N-4 (Fig. 2; Tables 2 and 3). Potential further separation was investigated using elemental bi-plots in combination with geographical and chronological data, but no further separation could be justified. The elemental weightings for the four groups are shown in the principal components analysis in Fig. 3. 55.96% of the variation falls along PC1, which divides N-3 and N-4 to the left with high iron oxide, titania and zirconia, from N-1 and N-2 to the right with high strontium. 17.62% of the variation is described by PC2, with higher alumina and silica to the top of the bi-plot, and higher lime and soda to the bottom. N-3 is separated from N-4, which has lower lime and higher alumina; while N-1 is distinguished from N-2, which has lower lime and soda, but higher silica.

Fig. 4 compares N1 – N4 with four glass compositional types previously identified from the region and period. Reference data (averages presented in Table 4) for the Levantine glass was provided by re-analysis of existing samples from the primary production site of Apollonia (Freestone et al., 2000) and the secondary workshop at Bet Shean (unpublished) representing "Apollonia-type" glass (Levantine I). Bet Eli'ezer glass (Levantine II) is represented by reanalysis of material from the primary production site of Bet Eli'ezer (Freestone et al., 2000). These new analysis were performed by LA-ICP-MS under the same conditions as campaign 1 and are presented in Appendix B (full data in supplementary material). Data from Egypt I and II are NAA analysis of samples from Gratuze and Barrandon (1990). The oxides used in Fig. 4 are the same as Fig. 3, however SrO was omitted as it was not available for the Egyptian reference samples. Groups N-1 and 2 are found to be identifiable as Levantine glasses, corresponding to Apollonia-type (Levantine I) and Bet Eli'ezer (Levantine II), while N-3 and N-4 match Egypt II and Egypt I glass groups respectively.

3.2. N-1 and N-2 - the Levantine glass

N-1 (54 samples) and N-2 (17 samples) form two groups of very similar glass. They are of similar colour, often pale blue (aqua) but greenish-blue on occasion. Chemically, both are characterised by sand sources low in oxides from heavy accessory minerals – titania, iron oxide, zirconia (see Fig. 5) – but relatively high in alumina (>3%) suggesting a mature high silica sand with significant feldspar content. Lime is high (7–9%), as is strontium oxide (~500 ppm), with a strong correlation between the two (Fig. 7), suggesting a marine sand with the lime predominantly present as shell (Freestone et al., 2003). The trace oxide distributions demonstrate that the two groups are extremely close geochemically (Fig. 5). This might be expected as glass production at Bet Eli'ezer and in the area of Apollonia used sands from a similar geological setting. Separation between the groups was accomplished using the major oxides soda, silica, lime and alumina, as shown in Fig. 7a and b. These graphs highlight differences in the lime/alumina ratios of the sands, reflecting the differing carbonate and feldspar contents (cf. Brill, 1988), as well as in the silica/soda ratio, which most likely represents differences in batch recipe (Freestone et al., 2000). Comparing the current data in Fig. 7a with reference data in Fig. 7b it is observed that N-1 most closely corresponds to Levantine I production from the site of Apollonia, and much less so to material from the production site of Jalame (Weinberg, 1988), while N-2 corresponds to Bet Eli'ezer/Levantine II. It is important to observe that the products of the site at Jalame, which were grouped by Freestone et al. (2000) with Apollonia as "Levantine I" are distinct from the Apollonia glass. These are identifiably distinct productions as the well-publicised recent discovery of primary production furnaces at Jalame by one of the authors (Y G-R) makes clear (http://www.antiquities.org.il/article_eng.aspx?sec_id=25&subj_

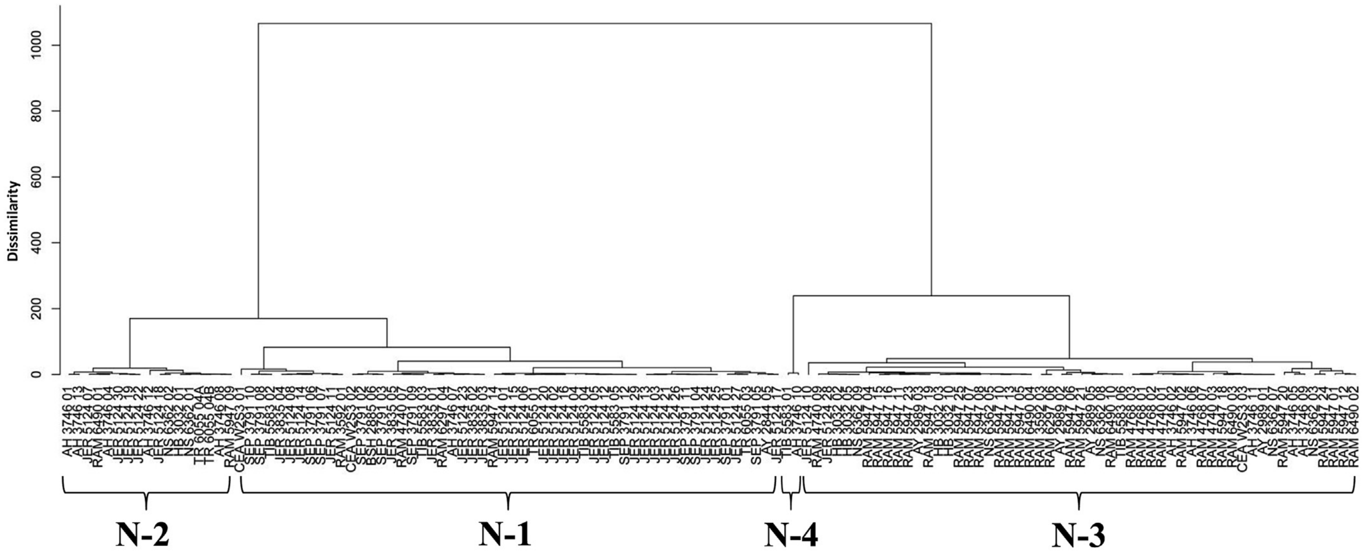

Fig. 2. *Cluster analysis (Ward's method) showing the four principal groupings. Determining oxides*: SiO_2, Al_2O_3, CaO, SrO, Fe_2O_3, TiO_2, ZrO_2 and Na_2O. (*N = 128; 5 samples* – AH 3746-03, NS 6362-04, NS 6362-10, RAM 5947-03, RAM, 5947-22 – removed as outliers).

Table 2
Mean and standard deviation for the identified groups. Major, minor and three selected trace oxides, weight % unless indicated. StDev = Standard deviation.

Group	Glass type	No.	Colour[a]		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO[b]	SrO[b]	ZrO_2[b]
N-1	Apollonia (Levantine I)	54	Pale blue	**Mean**	**14.31**	**0.56**	**3.17**	**71.33**	**0.10**	**0.83**	**0.62**	**8.37**	**0.08**	**0.48**	**276**	**498**	**60**
				StDev	*0.96*	*0.08*	*0.18*	*1.51*	*0.05*	*0.09*	*0.17*	*1.19*	*0.01*	*0.07*	*436*	*48*	*8*
N-2	Bet Eli'ezer (Levantine II)	17	Pale blue	**Mean**	**12.13**	**0.51**	**3.26**	**74.64**	**0.08**	**0.70**	**0.53**	**7.36**	**0.08**	**0.50**	**192**	**453**	**60**
				StDev	*0.90*	*0.08*	*0.21*	*0.80*	*0.02*	*0.07*	*0.12*	*1.08*	*0.02*	*0.11*	*26*	*38*	*11*
N-3[c]	Egypt II	52	Greenish-blue	**Mean**	**14.14**	**0.58**	**2.53**	**70.48**	**0.10**	**1.03**	**0.29**	**9.51**	**0.26**	**0.92**	**359**	**218**	**235**
				StDev	*1.15*	*0.20*	*0.25*	*1.01*	*0.03*	*0.11*	*0.14*	*0.85*	0.04	0.10	*489*	*51*	*46*
N-4	Egypt I	2	Greenish-blue	**Mean**	**17.06**	**0.83**	**4.46**	**70.94**	**0.08**	**0.98**	**0.43**	**2.71**	0.54	1.79	**405**	**219**	**255**
				StDev	*1.41*	*0.03*	*0.11*	*1.68*	*0.04*	*0.12*	*0.01*	*0.06*	*0.01*	*0.03*	*10*	*7*	*14*

[a] Most frequent colour.
[b] MnO, SrO and ZrO2 as ppm.
[c] Five Co and Mn de/coloured vessels removed from mean (see text).

id=240&hist=1). The use of the term 'Levantine I' has possibly masked these differences, potentially hindering the identification of individual production sites and new production groups. Therefore, it is recommended that the terms Levantine I and II be discontinued in favour of the term Levantine for production in the Levant, while compositional groups should be compared to and named after known production sites if compositional similarities are shown, e.g. Apollonia-type.

Table 3
Mean trace oxide composition of the four identified glass groups. Values as ppm. bdl = 1 or more samples below detection limit.

		B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	Y_2O_3	Nb_2O_3	MoO	SnO_2	Sb_2O_3	BaO	La_2O_3	CeO_2
N-1	**Mean**	**206**	**17.1**	**35**	**2.1**	**5.4**	**27.0**	**13.2**	**4.1**	**3.2**	**10.3**	**9.1**	**2.1**	**0.41**	**9.1**	**bdl**	**257**	**8.4**	**16.0**
	StDev	*65*	*2.9*	*30*	*1.2*	*1.3*	*48.1*	*6.8*	*0.4*	*5.9*	*1.6*	*0.7*	*0.3*	*0.20*	*14.8*	*bdl*	*21*	*0.8*	*1.6*
N-2	**Mean**	**160**	**16.5**	**44**	**bdl**	**5.1**	**9.3**	**9.8**	**4.1**	**1.8**	**9.7**	**8.7**	**2.2**	**0.36**	**12.9**	**bdl**	**251**	**8.2**	**15.8**
	StDev	*38*	*2.8*	*49*	*bdl*	*1.1*	*13.1*	*3.3*	*0.5*	*0.5*	*1.7*	*0.7*	*0.4*	*0.11*	*22.2*	*bdl*	*18*	*0.9*	*1.8*
N-3[a]	**Mean**	**270**	**35.7**	**51**	**3.7**	**7.6**	**17.9**	**22.7**	**3.7**	**2.3**	**5.0**	**8.4**	**4.5**	**0.18**	**14.2**	**bdl**	**174**	**8.4**	**16.2**
	StDev	*69*	*4.7*	*34*	*1.9*	*1.3*	*40.9*	*15.1*	*0.4*	*1.6*	*1.2*	*0.7*	*0.5*	*0.18*	*19.3*	*bdl*	*19*	*0.6*	*1.1*
N-4	**Mean**	**241**	**76.9**	**101**	**4.3**	**13.5**	**3.4**	**34.2**	**6.2**	**1.3**	**9.2**	**12.2**	**6.5**	**0.04**	**7.2**	**1.3**	**229**	**11.1**	**23.1**
	StDev	*52*	*0.6*	*4*	*3.9*	*0.3*	*1.0*	*0.0*	*1.0*	*0.0*	*0.3*	*0.0*	*0.0*	*0.04*	*9.2*	*1.7*	*18*	*0.1*	*0.04*

	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	HfO_2	Ta_2O_3	WO	PbO	ThO_2	UO_2
N-1 cont.	**1.91**	**7.5**	**1.51**	**0.43**	**1.28**	**0.22**	**1.30**	**0.28**	**0.74**	**0.10**	**0.68**	**0.10**	**1.30**	**0.11**	**0.07**	**54**	**1.04**	**1.09**
	0.13	*0.5*	*0.12*	*0.05*	*0.13*	*0.02*	*0.11*	*0.02*	*0.07*	*0.01*	*0.05*	*0.01*	*0.15*	*0.01*	*0.02*	*87*	*0.10*	*0.45*
N-2 cont.	**1.87**	**7.4**	**1.47**	**0.42**	**1.29**	**0.21**	**1.24**	**0.26**	**0.69**	**0.10**	**0.68**	**0.10**	**1.28**	**0.11**	**0.08**	**856**	**1.04**	**0.75**
	0.16	*0.5*	*0.12*	*0.06*	*0.12*	*0.02*	*0.10*	*0.02*	*0.06*	*0.01*	*0.06*	*0.01*	*0.19*	*0.02*	*0.01*	*2374*	*0.13*	*0.12*
N-3[a] cont.	**1.98**	**7.7**	**1.55**	**0.37**	**1.32**	**0.21**	**1.31**	**0.28**	**0.79**	**0.12**	**0.86**	**0.13**	**4.98**	**0.25**	**0.09**	**92**	**1.82**	**1.14**
	0.14	*0.6*	*0.13*	*0.04*	*0.14*	*0.02*	*0.14*	*0.03*	*0.08*	*0.01*	*0.09*	*0.01*	*0.99*	*0.03*	*0.05*	*285*	*0.21*	*0.19*
N-4 cont.	**2.74**	**11.4**	**2.35**	**0.60**	**2.06**	**0.34**	**2.04**	**0.42**	**1.13**	**0.17**	**1.24**	**0.18**	**5.41**	**0.34**	**0.09**	**5**	**2.40**	**1.52**
	0.00	*0.6*	*0.06*	*0.10*	*0.01*	*0.00*	*0.13*	*0.01*	*0.03*	*0.01*	*0.01*	*0.00*	*0.02*	*0.03*	*0.00*	*2*	*0.16*	*0.04*

bdl = 1 or more samples below detection limit.
[a] Five Co and Mn de/coloured vessels removed from mean.

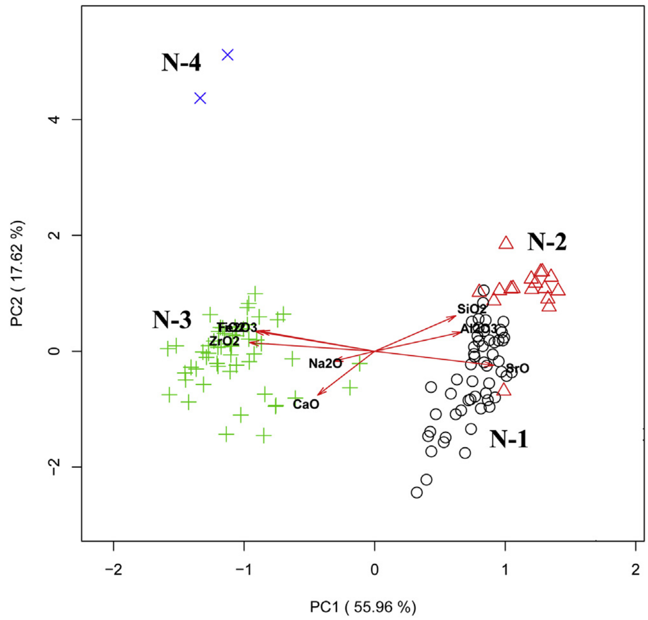

Fig. 3. *PCA bi-plot of principle components 1 and 2. Groups labelled as* Fig. 1. *Determining oxides*: SiO_2, Al_2O_3, CaO, SrO, Fe_2O_3, TiO_2, ZrO_2 and Na_2O.

3.3. N-3 and N-4 - the Egyptian glass

Groups N-3 (57 samples) and N-4 (2 samples) are characterised by sand sources much higher in the heavy accessory minerals, showing considerable quantities of iron oxide (1–2%), titania (0.3–5%) and zirconia (200–300 ppm), as well as a higher Nb and slight heavy rare-earth enrichment when compared to Apollonia- and Bet Eli'ezer-type glasses (Fig. 5). The high iron oxide and titania correspond with the typically high values found in sands in Egypt and in Egyptian glass (Nenna, 2014, 179; Foy et al., 2003a, 45), furthermore, the high soda content seen in N-3 and N-4 is also typical of Egyptian glasses probably due to their closer proximity to

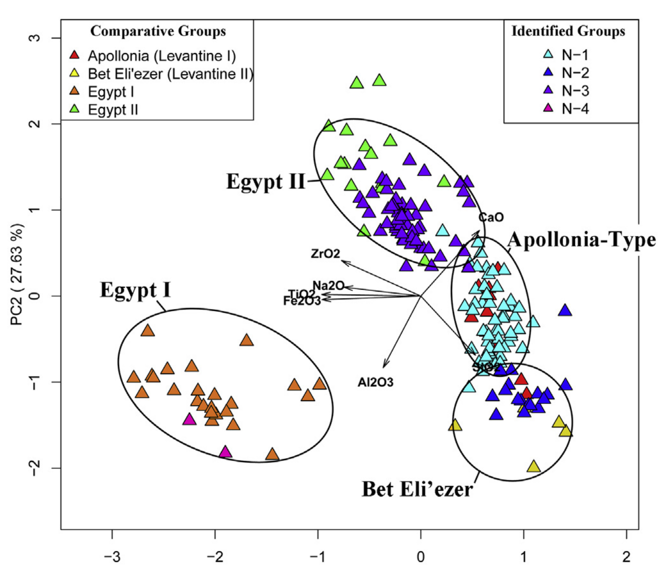

Fig. 4. *PCA bi-plot of present data against known literature groups using principal components 1 and 2. Labelled circles added manually. Oxides as* Fig. 3 but omitting SrO (see text).

the natron source.

N-3 and N-4 are distinctly separate glass groups made of different raw materials, despite their potential shared Egyptian origin. N-3 vessels are predominately greenish-blue to green in colour and made of an Egypt II type glass, as demonstrated by comparison with reference material in Fig. 4 and demonstrated by the close similarity in ZrO_2:TiO_2 ratio (Gratuze and Barrandon, 1990) shown in Fig. 8. Analogous to previously analysed Egypt II, N-3 has relatively low amounts of alumina (2–3%), high lime (9–10%), and a low SrO/CaO oxide ratio (Fig. 6), suggesting that the lime is derived from a limestone source rather than beach sand (Freestone et al., 2003). The production origins of this group are unknown, but in addition to coin weights from Fustat (Gratuze and Barrandon, 1990), other appearances of this glass type include a secondary workshop at El Ashmunein, Middle Egypt (Bimson and Freestone, 1985), 61 samples identified as Group N2-b from Raya, South Sinai, dating mainly to the 9th century (Kato et al., 2009, 1705), and 18 samples of Abbasid dated glass from Tebtynis and Fustat, Egypt, labelled as Group 7 (Foy et al., 2003b). Group N-3 is unusual in containing the only vessels analysed in this study with added cobalt or manganese. These amounted to five samples in total. They were removed from the average in Tables 3 and 4 as their compositions had been modified relative to the typical N-3 composition, although they are readily identifiable as this glass type. Individual results can be found in Appendix A. Three of these samples – RAM 3592-03, RAM 6297-06 and TIB 5583-06 – were dark blue with ~600 ppm added cobalt. These had accompanying increases in iron oxide (0.3–0.5% above N-3* mean), copper oxide (~1000 ppm) and zinc oxide (~700 ppm). The first two samples are incised decorated and the last was a small 'shoe-shaped' bottle. The final two samples – NS 6362-08, a tonged colourless vessel of unknown type and JER 5124-28, a pale-green mould-blown bowl – were manganese oxide decolourised, having 1.4% and 0.9% MnO respectively, with which the only identifiable associated compound was barium oxide at ~100 ppm above the N-3* mean.

Group N-4 consisted of only 2 samples, greenish-blue in colour, and of a distinctive composition matching that of Egypt I glass as identified by Gratuze and Barrandon (1990). The similarities are demonstrated in Fig. 4 and with further matches seen in the ZrO_2/TiO_2 ratio (Fig. 8). N-4 has a much higher complement of REE than the other glasses (Fig. 5), which is matched by the highest amounts of iron oxide and titania of any group, as well as high alumina (4–5%). Lime is distinctly low (2–3%), but so is strontium oxide, so that the SrO/CaO ratio corresponds with that of groups N-1 and N-2, suggesting lime from shell-containing coastal sand. The production origins for Egypt I glass have been suggested to the Wadi Natrun (Freestone et al., 2000, 72), and while glass with low lime has been found in this location from earlier periods (Picon et al., 2008), no production evidence for the Islamic period has yet been uncovered (Nenna, 2014, 2015). Production in the Egyptian Delta is a possibility, with a coastal location being suggested by the SrO/CaO ratio. N-4 is similar to Foy et al.'s (2003b) Groups 8 and 9 of Umayyad period glasses from Tebtynis and Fustat, Egypt.

3.4. Chronological development

The samples are divided into six chronological groups. The percentage frequency of compositional types is plotted against these groups in Fig. 9 to examine change through time. The occurrence of plant ash glass samples is also shown as a general category but these are not be discussed in detail here. Most of the groups are separated by century, however the 8th century is subdivided into early-mid and mid-late 8th around the Umayyad-Abbasid dynastic change in 750. It must be emphasised that there is likely to be a great deal of overlap and blurring between these

Table 4
Mean chemical composition showing major, minor and selected trace oxides for the known literature groups. Weight % unless indicated. StDev = standard deviation.

Type	No.	Date	Analysis		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO[b]	SrO[b]	ZrO_2[b]
Apollonia-type (Levantine I)[a]	10	6-7th century	LA-ICP-MS	**Mean**	**14.51**	**0.64**	**3.03**	**71.60**	**0.08**	**0.83**	**0.49**	**8.14**	**0.08**	**0.46**	**195**	**495**	**53**
				StDev	*1.15*	*0.11*	*0.22*	*1.64*	*0.04*	*0.09*	*0.10*	*0.76*	*0.01*	*0.04*	*9*	*45*	*7*
Bet Eli'ezer (Levantine II)[a]	5	7-8th century	LA-ICP-MS	**Mean**	**11.56**	**0.52**	**3.32**	**76.20**	**0.07**	**0.67**	**0.44**	**6.42**	**0.10**	**0.57**	**189**	**418**	**59**
				StDev	*1.18*	*0.03*	*0.18*	*1.22*	*0.01*	*0.12*	*0.11*	*0.77*	*0.04*	*0.21*	*30*	*50*	*11*
Egypt I[c]	24	7-8th century	NAA	**Mean**	**18.25**	**0.93**	**4.05**	**70.05**	**n/a**	**0.95**	**0.40**	**3.03**	**0.50**	**1.74**	**514**	**n/a**	**246**
				StDev	*1.38*	*0.14*	*0.29*	*1.21*	*n/a*	*0.14*	*0.11*	*0.23*	*0.12*	*0.28*	*70*	*n/a*	*65*
Egypt II[c]	17	8-9th century	NAA	**Mean**	**17.26**	**0.58**	**2.19**	**67.85**	**n/a**	**1.07**	**0.32**	**9.34**	**0.27**	**0.98**	**302**	**n/a**	**220**
				StDev	*1.96*	*0.13*	*0.35*	*1.90*	*n/a*	*0.18*	*0.24*	*1.27*	*0.06*	*0.23*	*146*	*n/a*	*80*

[a] LA-ICP-MS data from the reanalysis of samples from Apollonia and Bet Elie'zer (Freestone et al., 2000) and Bet Shean (unpublished). Full data in Appendix B.
[b] ppm.
[c] Data from Gratuze and Barrandon (1990).

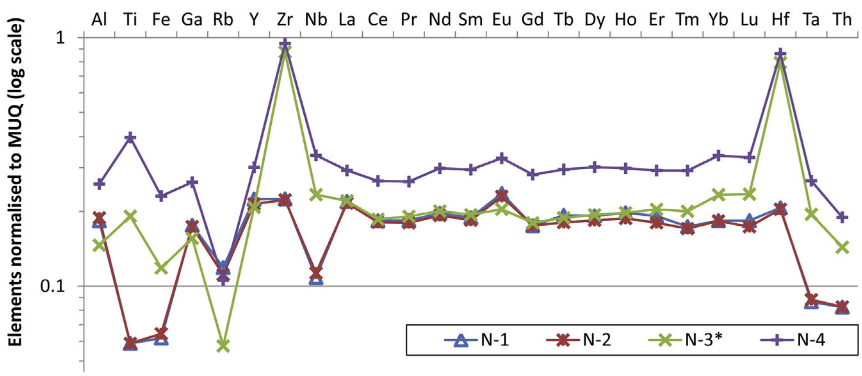

Fig. 5. Group means of selected trace and REE data normalised to weathered contineneṭal crust (MUQ; Kamber et al., 2005). Log scale. * = Co and Mn coloured samples removed from this group.

chronological categories and that the partitioning between groups is unlikely to be exact. Furthermore, the absolute vessel amounts in each period are influenced by sampling strategy and site context, and may not necessarily reflect relative abundances; however, ratios between sites are likely to be informative. While cognisant of these limitations, the examination of the data reveals a number of trends of apparent significance.

The 7th century material comprised of glass mainly from the Wilson's Arch and Great Causeway excavation in the Old City, Jerusalem (A-5125) dated through style and context – although some material likely continues in date to the early 8th century – and from sealed contexts in early Umayyad occupation layers in Sepphoris. Smaller amounts also came from Caesarea, Tiberias, Tel Rosh and a single sample from Ramla (RAM 3592-01; a stemmed wine glass stylistically Byzantine but found in a later context). Vessels from this time period consisted of a variety of types, including oil lamps, wine glasses, bottles and bowls, some with applied trails or rarely tonged, pinched or stamped decoration. They were mainly pale blue and greenish-blue in colour. Compositionally, the 7th century was dominated almost entirely by Apollonia-type glass. Only a single vessel, TIB 5583-01, a greenish-blue bowl with pinched decoration, came from a different group of Egypt I glass. The glass supply of this period appears to be dominated by local production of a glass type similar to Byzantine production (Tal et al., 2004; Freestone et al., 2008). The 7th century samples of N-1 post-date the 6th century furnaces so far identified at Apollonia (Freestone et al., 2000; Tal et al., 2008). This therefore suggests that either later as yet unidentified furnaces existed at Apollonia, or further production sites were operating nearby using similar sands and a similar glass recipe during the 7th century.

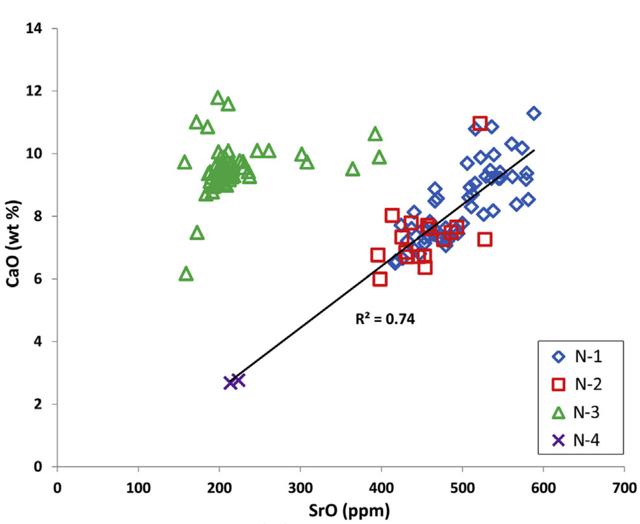

Fig. 6. CaO vs SrO bi-plot of the four identified groups. Trend line for groups N-1, N-2 and N-4.

The early 8th century saw dramatic change and diversification of the glass supply in Palestine. The vessels from this period are Umayyad forms, and identified mainly from Ramla (founded c.715) and Ahihud (dated by associated ceramics to the 8th century; see Porat and Getzov, 2010), with smaller amounts of material from Ha-Bonim, Jerusalem, Nahal Shoval and other sites (see Appendix C). As before, potential overlap with succeeding chronological categories is a possibility in some cases due to long-lived forms or poor stratigraphic resolution. The vessels were mainly bowls, beakers, bottles, with a range of decorative types – mould blown, trailed, wheel cut, tonged and pinched. This period saw quantities of

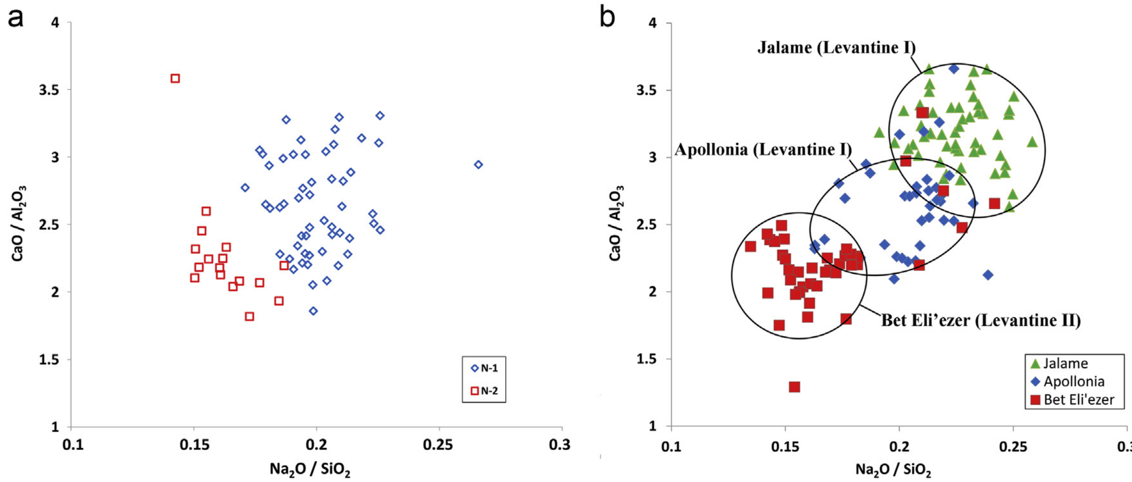

Fig 7. a (left). CaO/Al_2O_3 vs. Na_2O/SiO_2 bi-plot demonstrating the separation between Levantine groups N-1 and N-2. Fig. 7b (right). Comparative data from the three known primary production sites – 4th century Jalame (Brill, 1988); 6–7th century Apollonia (Freestone et al., 2000, 2008; Tal et al., 2004) and 8th century Bet Eli'ezer (Freestone et al., 2000).

Apollonia-type glass fall dramatically to only 4 samples (8%), while 14 samples (28%) from five sites are of a Bet Eli'ezer type glass which is seen for the first time. This suggests that production along the coast near Apollonia ceased and was replaced by that at Bet Eli'ezer-Hadera. The higher silica/lower soda content of this glass type also indicates a change in recipe, the reduction in natron content possibly suggesting a shortage (Freestone et al., 2000). Furthermore, a substantial influx of Egyptian glass occurred at this time, with the remaining 34 samples (62%), comprising the majority of the glass of this period, corresponding to an Egypt II type. A distinct shift in the industry is clearly indicated, with Apollonia-type glass being replaced by new production with lower soda and the import of glass of a likely Egyptian origin.

In the mid-8th century the ruling dynasty changed from Umayyad to Abbasid. A small number of vessels could be dated to this late 8th century transitional period through specific forms and contexts. These vessels were predominantly from Ramla, but also from Jerusalem (A-3835), Ha-Bonim and Tel Rosh. These vessels show Egypt II glass continuing to be an important constituent of the glass supply in Palestine, but at the expense of Levantine glass, which is present in much reduced amounts. This suggests a possible downturn in glass production at Bet Eli'ezer, although the number of vessels analysed in this period may be too small to be fully representative. Of particular note for this time period is the occurrence of the earliest plant ash glass; 6 samples from a variety of sites and of more than one compositional group. This is an important development as it is the earliest plant ash glass recognised from Islamic period Palestine. The types and origins of this glass are discussed elsewhere (Phelps Forthcoming). It is noted that these are currently the earliest plant ash glass samples to be recognised from Islamic Palestine and are similar in date to plant ash glass from Raqqa, Syria (Henderson, 1995, 1999).

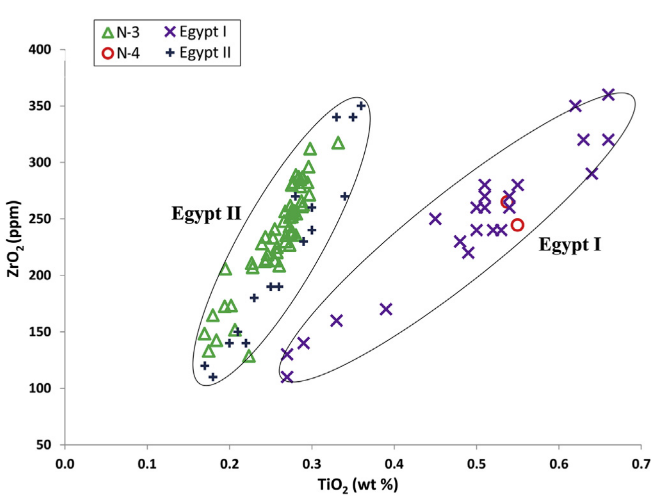

Fig. 8. ZrO_2 vs. TiO_2 bi-plot demonstrating the similarity of the Egyptian groups N-3 and N-4 to Egypt I and II (Gratuze and Barrandon, 1990).

The 9th century is the last period in which natron glass is evident in any significant quantity. 14 natron glass samples are identified from six sites, including Nahal Shoval, Jerusalem and Ashdod-Yam. An additional three samples come from less precisely dated contexts from the 9th-early 11th century, and in the absence of more specific dating have been added evenly to the 9th and 10th century groups. There are three notable features of the glass of this period. Firstly, Levantine natron glass is present in just two samples (JER 5124-29 and 30), both from the same context (L1516). There is the possibility that these shards were either residual, misdated, legacy items or recycled, although these compositions do not show obvious signs of recycling (e.g. enrichment in colourant elements; see Freestone et al., 2002). It seems likely that natron glass production in Palestine had ceased by this time. It is also relevant to note that Egypt II glass continues to be seen, implying continued production and import.

The 10th century finds even Egyptian natron glass to be in abeyance, suggesting that import from and possibly production in Egypt, had finally discontinued. Significant production of Egyptian natron glass had outlasted Levantine production by up to 100 years. These later samples of Egypt II include the cobalt coloured scratch decorated vessels RAM 6297-06 and the two manganese decoloured samples, JER 5124-28 and NS 6362-08, possibly suggesting preferential imports of higher value glass. The results show that plant ash glass production quickly grew to dominate glass supply in Palestine from the 9th century onwards. As seen from the period under examination natron glass does not reappear in significant quantities after this point.

4. Discussion

This investigation has highlighted three major developments in

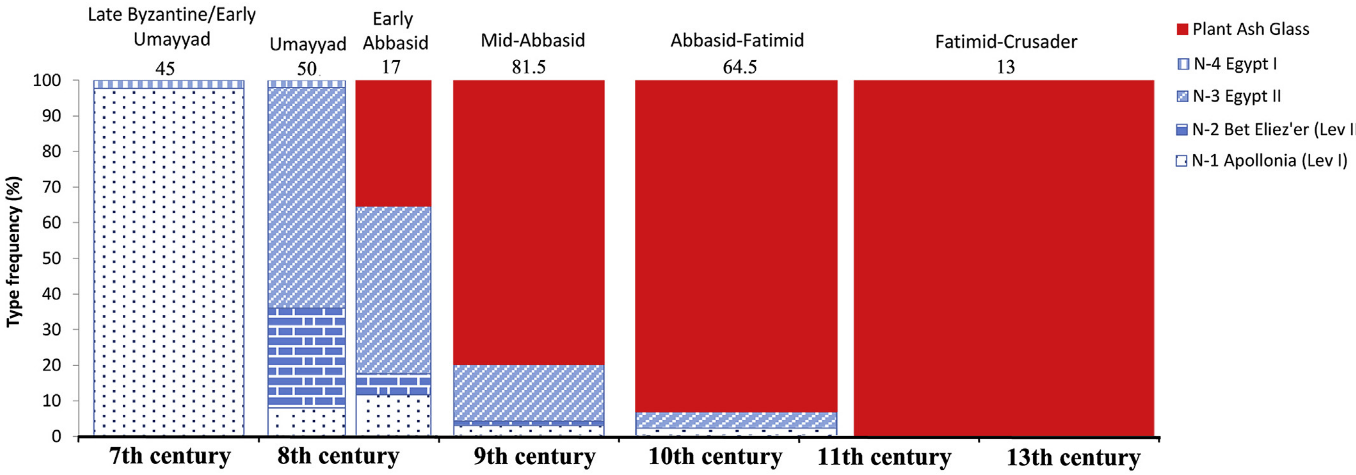

Fig. 9. Histogram plotting percentage frequency of vessel compositional type against time. Number of vessels shown at top of each column. Plant ash glass (discussed in Phelps Forthcoming) added for comparison.

the Palestinian glass industry principally occurring during the 8th century: a relatively abrupt change in the production location and recipe of Levantine natron glass; an influx of imported Egyptian glass; and the appearance of plant ash glass. The latter two of these are possibly symptomatic of the declining availability of natron in the Levant as seen from the reductions in glass soda content from the middle of the first millennium noted by a number of authors (Fischer and McCray, 1999, 904; Freestone et al., 2000; Henderson, 2002, 598) and as described here. This section evaluates the potential reasons for the above changes.

The production of natron glass in Palestine appears to continue unabated after the conquest in 640 CE. It is reported by many that conquest had little effect on people's everyday lives (Milwright, 2010a, 44; 2010b, 666) with no destruction layers (Whitcomb, 1998, 488; Walmsley, 2007, 47), no changes to settlement patterns (see Magness, 2003) and negligible changes to material culture in ceramics (Schick, 1998, 94, Walmsley, 2007, 53) and glass (Carboni, 2001, 15; Brosh, 2003, 319). The production of glass appears similarly unaffected with Byzantine compositional types continuing. It is only in the late 7th/early 8th century with the disappearance of Apollonia-type glass that the first break in Byzantine production is seen. The centre of Palestinian glass production appears to move to Bet Eli'ezer, a site situated farther north and about 8 km inland. Here it would have still been possible to bring beach sand for use, or possibly *kurkar* (fossil beach sand) was exploited. The timing of this change coincides with the influential reforming reigns of Caliph al-Malik (r. 685-705) and al-Walid (r. 705-15). Al-Malik in particular increased the centralisation of the state during this reign, reforming the administration (Hawting, 1986, 61–68; Donner, 1986, 293) and changing official language of the bureaucracy to Arabic (Robinson, 2010, 218-9). He also produced the first Islamic coinage, a new system of weights and measurements (Schick, 1998, 95-6; Walmsley, 2007, 59–64), and oversaw the completion of the very first Muslim monument, the Dome of the Rock, in 692 (Johns, 2003, 416). This period was also when the first distinct Islamic material culture started to be produced, with changes seen in ceramics (Walmsley, 2007, 53) and glass (Brosh, 2003, 333; Hadad, 2005, 78). Thus, the changes evident in glass production appear to coincide with political, cultural and social changes also occurring in the early 8th century.

A number of potential factors can be proposed as to why production around Apollonia was abandoned in favour of Bet Eli'ezer. The conquest cut Palestine off from Mediterranean trade with Southern Europe and the Byzantine Empire, but in turn opened routes into former Sasanian territories. This shifted the focus of trade inland and eastwards (Morony, 2004). The 7th century also saw raiding by the Byzantine navy (Avni, 2014, 321), which resulted in depopulation of coastal regions. A culmination of this was the occupation of Caesarea between 685 and 695 (Peterson, 2005, 86). Not only would this have increased the risk of coastal operations but combined with the loss of contact with overseas markets would have removed some of the benefits of such a location, therefore encouraging a more inland site with good road networks. Furthermore, the higher silica content of the glass produced at Bet Eli'ezer would have required higher furnace operating temperatures, thereby needing greater quantities of fuel. It has been noted that the environment around Bet Eli'ezer was forested and supported plentiful supplies of wood (Gorin-Rosen, 2000, 52) while Apollonia, near the coast, did not (Tal et al., 2004, 61). Therefore a combination of factors, including the requirements for fuel, may have encouraged the move to Bet Eli'ezer.

Production at Bet Eli'ezer appears to be large scale and well organised with 17 tank furnaces, some arranged in banks. The excavated furnaces are also situated within a larger zone of glass production dotted around the surrounding area (Gorin-Rosen, 2000, 54). This larger scale operation is in apparent contrast to Apollonia where the tank furnaces so far excavated appear to be singular, although it is unlikely that more than one or two furnaces were in concurrent use at Bet Eli'ezer. Nonetheless, intensive glass production at Bet Eli'ezer may signify a change in how production was being organised or in the ownership of the site – maybe a change to state involvement during the Islamic period –, although it could be related to greater fuel availability, thereby reducing the need to spread production across a wider geographical area to access resources. Glassmaking at Bet Eli'ezer itself appears to have been short-lived, suggested at just a few seasons (Gorin-Rosen, 2000), although production in the surrounding areas may have continued for longer. This study suggests that the Bet Eli'ezer compositional type was in production for only 50–100 years at the most, ending in the late 8th/early 9th century. This is a relatively short lived compositional group in contrast to Apollonia-type glass which was produced from the 6th to late 7th century. However, despite the seemingly large scale, intensive and well organised operation at Bet Eli'ezer, this glass type has not been reliably identified beyond the eastern Mediterranean. This is in contrast with other Levantine types that were widely exported during the

Byzantine period (Ceglia et al., 2015; Freestone et al., 2002; Foy et al., 2003a). What were the reasons for the limited distribution? It could be due to the post-conquest changes in trade routes, which, as mentioned above, saw the decline in Mediterranean trade. This is evidenced by a lack of shipwreck finds and in pottery distributions (Kingsley, 2009, 35; McCormick, 2012). It could also be that less glass was being produced, possibly as a consequence of restrictions in the supply of natron (discussed below) and therefore glass was not available for export once local needs were met. It is further noted that the glass from Bet Eli'ezer, being lower in soda, was harder to work, and therefore might have been considered of lower quality glass and less attractive than alternatives. Bet Eli'ezer glass was therefore, possibly used more for local use and not exported. Investigations of ceramic vessel distributions in Palestine during the 8th century similarly shows localised distribution patterns of pottery made in Palestine (see Walmsley, 2012; Holmqvist and Martinón-Torres, 2011), however it must be noted that the organisation of the glass and ceramic industries were different with glass traded as raw chunks and less so as vessels.

A few studies on sites beyond Palestine have reported glass of a Bet Eli'ezer type. Large quantities are mentioned from 8th century Raya, Egypt (Kato et al., 2009; Shindo, 2007, 100). However, the absence of data for soda and silica, which are key diagnostic oxides in the differentiation of Bet Eli'ezer and Apollonia glass types (see above), mean the identification of Bet Eli'ezer glass cannot be confirmed. The average lime content (8.28%; Shindo, 2007, 1703) is more consistent with an Apollonia-type glass, alternatively suggesting that this is a late shipment of glass produced in the region of Apollonia, rather than glass of a Bet Eli'ezer type. Whatever the precise character of the Raya Levantine group, it does however indicate that some glass was moving south from Palestine to Egypt as well as from Egypt into Palestine during periods of the 8th century.

Raqqa, Syria (Henderson et al., 2004), also produced vessels using Levantine glass. This glass dates to the late 8th/early 9th century and has been confirmed as Levantine by isotopic analysis (Henderson et al., 2005, 670). However, this glass does not conform to Bet Eli'ezer production, nor does it precisely match Apollonian-type glass. The appearance of large quantities of Levantine glass with relatively high soda levels (13.8% Na_2O at Raqqa to 12.1% at Bet Eli'ezer) at this late date presents a contradiction to a suggested narrative of a contracting industry in Palestine due to natron shortages. Assuming that the analyses are compatible, this potentially suggests that an alternate production less affected by a restriction in the natron supply was operating in the late 8th century. It is also noted that the glass at Raqqa was used for state building projects (e.g. Harun al-Rashid's palaces; Henderson, 1999). This might imply state organised production and therefore one potential explanation is that this glass was a specifically ordered commission and was atypical of the industry as a whole. Another possibility is that the Raqqa used recycled imported Levantine cullet, rather than fresh production.

Regarding recipe change, both the present analyses of vessels and the analysis of raw glass from the Bet Eli'ezer production site demonstrate that this production was characterised by a recipe containing low quantities of soda – up to 20% less than the preceding Apollonia-type glass – and this has been suggested to indicate falling natron supply in Palestine (Freestone et al., 2000). There are a number of potential explanations for the decline in availability of natron. A breakdown in Eastern Mediterranean trade has already been acknowledged, which is supported by a lack of shipwrecks between the 7–9th century (Kingsley, 2009, 35). However, as shown above, Egyptian glass was being imported, and there are numerous finds of Egyptian pottery at various sites in Palestine during the Umayyad and Early Abbasid period (see Taxel and Fantalkin, 2011). This demonstrates that Egyptian trade does not seem to have been affected, and implies that an explanation based solely on trade disruption is unlikely. Moreover, the use of reduced soda recipes continues for a relatively long period without improvement, suggesting long term rather than short term factors which are more likely to be related to issues concerning the natron source itself. These changes do not seem to have impacted upon the Egyptian industry, presumably due to its closer proximity and easier access to the raw material. As the Levantine industry declined due to this shortage, Egyptian glass was in a strong position to fulfil demand in the Palestinian glass market.

The relatively high quantities of compositionally Egyptian glass that start to emerge during the 8th century is one of the more surprising findings of this study. Egypt II glass was the most abundant type during this century, found at almost every site with contexts of this date, particularly at Ramla. There is evidence for the working of Egyptian glass (Egypt II) possibly alongside Levantine types (Bet Eli'ezer type) from a workshop in Tel Aviv (Freestone et al., 2015). Large quantities of Egyptian pottery also appear during this period, as seen from sites such as Jerash, Jordan (Morony, 1995, 18), Sepphoris, Ramla, Caesarea (see references within Taxel and Fantalkin, 2011), and therefore glass may have formed part of a wider economic expansion of Egypt. Locally made glass, due to inherent transport costs, would normally always be cheaper and more available, therefore the extensive use of Egyptian glass in Palestine suggests that a change in the Levantine industry was occurring, possibly through a contraction of production due to natron shortages, or increased costs of the glass, or a possible preference for Egyptian glass due to its superior working properties (Freestone et al., 2015). Furthermore, Egyptian glass was of a different colour (greener) and there might also have been a changing aesthetic preference at this time.

Nonetheless, Egyptian dominance of glass supply was short lived. By the 9th century Egyptian natron glass appears in smaller quantities and in the 10th century makes no significant contribution to the glass supply. This downturn correlates with other studies that suggest that natron glass production in Egypt ended around the mid-9th century (Sayre and Smith, 1974; Gratuze and Barrandon, 1990). However, Fischer and McCray (1999) reported continued use and dominance of natron glass into even later Islamic periods in glass from Sepphoris, their conclusion was based on six samples covering the 10th to 15th century and in the light of the present results it might be suggested that the sample set was not fully representative. From a Palestinian perspective, the end of Egyptian natron glass production appears to occur approximately 50–100 years after the end of the Levantine natron glass industry and might be similarly related to restrictions in natron supply.

Shortland et al. (2006) and Whitehouse (2002) have suggested a number of factors that may have triggered a shortage in natron, of which the favoured was political instability in the Delta region during the early 9th century. However, present results suggest that the decline in natron availability started earlier and occurred over a longer time scale than has previously been recognised, and only became severe enough to stop Egyptian production during the 9th century. Short term factors such as periods of weather fluctuation, trade disruption or political instability are unlikely to have caused these long term and permanent changes. Instead, long term factors, with gradual effects are more probably. Such as environmental change (Foy and Nenna, 2001; Picon et al., 2008), which might have restricted natron formation, and influences of cultural and societal development (Henderson, 2013), which might have led to the use of natron for other purposes, such as soap, detergents, or medicines (see Bingley, 1821, 128; Forbes, 1965, 182-2; Lovejoy, 2002, 29), reducing quantities available for glassmaking. Supply issues with natron seem to have come to a head in the 9th century. There is documentary evidence that reports new natron sources at Lake

Tarabiya, Upper Egypt, being exploited for the first time in the 9th century (during the reign of Tulun; Lane-Poole, 1901; Lucas, 1948, 299), although the location of this site is disputed (see Décobert, 2003). There is also evidence for state monopolisation and taxation of the industry at around the same time (Bianquis, 1998, 92; Lane-Poole, 1901, 43). The exploitation of new natron sources may be evidence that the supply of natron from the Wadi Natrun had become insufficient for demand. This combination of falling natron supply and rising demand alongside state control and increased prices through taxation may have signalled the end of natron use in glass production.

The contraction of natron glass production in the Levant appears to have encouraged the adoption of plant ash glass technologies, which very quickly rose to dominant glass supply. Plants suitable for the production of alkaline ashes were ubiquitous in the Near East (Ashtor, 1992), and their use would have offered a number of clear advantages. Firstly, they were more accessible for local and regional production, eschewing the necessity for transport over long distances. Furthermore, their widespread availability meant that plant ash glasses could be made with an increased flux content, making vessels cheaper to produce by lowering the melting temperature and also making the glass easier to work. The adoption of plant ash glass production in Palestine is therefore likely to have resulted from the need to develop a cheaper alternative to imported natron and Egyptian glass.

5. Conclusions

This paper presents a new and substantial dataset of major, minor and trace element analyses of early Islamic glass from Palestine. The use of well-contextualised glass vessels has allowed the elucidation of a series of significant changes in glass production and supply during the early centuries following the Arab conquest. The 8th century, in particular, saw a break with the Byzantine industry leading to recipe change, contraction in the glass industry, an influx of Egyptian glass and the adoption of plant ash glass technology. This project has dated the end of Levantine natron glass production, which had spanned over 1000 years, to the late 8th century. Furthermore, it dates the decline of Egyptian natron glass production to the 9th century, corroborating previous investigations based upon glass weights.

It appears that a restricted supply of natron is reflected in the compositions of the early 8th century Levantine glass which led to a decline in Palestinian production. It implies that the adoption of a plant ash flux is unlikely to be the result of short-term or cataclysmic events, as has been suggested in some previous work (Shortland et al., 2006; Whitehouse, 2002), but longer term factors, such as climate change (Foy and Nenna, 2001; Foy et al., 2003a; Picon et al., 2008) or the expansion of the use of natron for purposes other than glass production. These conditions worsened until the 9th century when natron glass production in Egypt also ceased, around 100 years after production in Palestine. The developments in the glass industry documented here occurred during a period of immense change in the Near East. In the late 7th/early 8th century political and economic reforms established under al-Malik (r. 695-705) and al-Walid (r. 705-15) resulted in a growth in Islamic identity and cultural development. The mid-late 8th century in turn saw the founding of the Abbasid dynasty and movement of the capital eastwards to Baghdad, opening up material culture of the Near East to increased Sasanian/Persian influences. The changes in glass technology and the adoption of plant ash glass appear to coincide with these developments, but the mechanisms by which these cultural and political changes affected the glass industry are still to be fully understood.

Further analyses are required from a wider geographic area outside of Israel to confirm a pattern of contraction in the Levantine industry suggested here. Samples from the 8–9th centuries are particularly under-represented in the literature. This paper has also highlighted separation within the Levantine I compositional group, and it is recommended that the terms Levantine I and Levantine II be discontinued in favour of the use of production sites – Jalame, Apollonia and Bet Eli'ezer – where possible, and that "Levantine" serves as a general term for glass from this region. This work also emphasizes a need for the analysis of glass from well characterised contexts, which, alongside archaeological investigation of other suspected primary production sites and coupled with more accurate and precise analytical techniques, should allow further refinement of our understanding of glass production during this important transitional period.

Acknowledgements

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Appendix A. Samples sorted by compositional group.

Major, minor and selected trace oxides. Full data can be found in the supplementary material as Appendix A (online).

		Major and minor elements as wt %									Selected trace elements as ppm							
Apollonia-type		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Fe_2O_3	B_2O_3	MnO	CoO	SrO	ZrO_2	Sb_2O_3	BaO	PbO
AH 3746 07	N-1	13.36	0.70	3.16	72.20	0.15	0.55	8.30	0.08	0.46	241	169	bdl	511	53	2.75	268	5
AY 2844 05	N-1	15.61	0.62	3.17	70.02	0.06	0.84	8.18	0.06	0.37	360	220	1.5	538	47	0.57	248	7
BSH 2885 06	N-1	13.37	0.67	2.91	71.72	0.18	0.85	8.69	0.08	0.49	275	257	3.8	512	59	2.73	234	45
CEA W2S3 01	N-1	17.63	0.68	3.20	66.30	0.15	1.00	9.41	0.07	0.42	333	227	3.5	547	50	0.40	253	29
CEA W2S3 02	N-1	13.10	0.66	3.07	73.06	0.06	0.41	8.12	0.09	0.53	194	194	2.3	440	65	0.00	232	12
JER 3835 01	N-1	12.29	0.57	3.34	71.89	0.16	0.85	9.26	0.08	0.49	220	220	2.5	562	59	bdl	282	12
JER 3835 02	N-1	12.99	0.59	3.14	71.90	0.08	0.59	9.21	0.08	0.49	214	244	5.5	536	60	0.30	258	40
JER 3835 03	N-1	13.57	0.63	3.11	71.19	0.07	0.50	9.37	0.07	0.43	255	254	3.1	579	56	0.60	296	18
JER 3835 04	N-1	15.13	0.57	3.09	69.31	0.11	0.48	9.69	0.07	0.47	225	184	1.7	506	52	0.05	248	30
JER 3835 05	N-1	13.79	0.69	3.41	69.92	0.12	0.68	9.27	0.11	0.67	285	3381	3.8	529	64	2.69	282	52
JER 5124 01	N-1	14.81	0.46	3.26	72.55	0.05	0.52	6.80	0.09	0.50	143	190	1.9	447	67	0.45	261	188
JER 5124 02	N-1	14.33	0.42	3.21	72.68	0.05	0.56	7.28	0.07	0.39	157	173	1.5	474	55	0.05	265	5

(continued on next page)

(*continued*)

		Major and minor elements as wt %									Selected trace elements as ppm							
Apollonia-type		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Fe_2O_3	B_2O_3	MnO	CoO	SrO	ZrO_2	Sb_2O_3	BaO	PbO
JER 5124 03	N-1	15.35	0.43	3.04	72.16	0.05	0.52	6.93	0.07	0.39	157	168	1.5	441	57	0.05	250	6
JER 5124 04	N-1	14.01	0.53	3.53	71.72	0.06	0.49	8.06	0.11	0.63	157	229	2.4	526	76	0.04	268	7
JER 5124 05	N-1	13.98	0.50	3.25	72.72	0.07	0.43	7.61	0.10	0.54	144	218	2.1	437	66	0.05	261	5
JER 5124 06	N-1	14.25	0.52	3.14	72.24	0.06	0.55	7.77	0.08	0.44	161	186	1.7	500	60	0.04	267	7
JER 5124 08	N-1	15.61	0.65	3.05	69.29	0.05	0.39	9.47	0.10	0.51	219	202	2.0	534	73	0.00	240	4
JER 5124 11	N-1	14.40	0.68	3.13	68.84	0.18	0.89	10.31	0.10	0.54	239	229	3.6	561	70	0.84	260	21
JER 5124 12	N-1	14.28	0.48	3.27	72.72	0.06	0.53	7.21	0.10	0.54	132	202	2.1	432	72	0.09	258	46
JER 5124 13	N-1	15.16	0.45	3.03	72.58	0.06	0.58	6.65	0.08	0.41	151	174	1.6	426	61	0.03	252	4
JER 5124 14	N-1	14.98	0.59	3.18	70.02	0.05	0.47	9.18	0.10	0.56	174	232	2.2	579	65	0.03	264	8
JER 5124 15	N-1	14.52	0.49	3.20	73.18	0.05	0.51	6.57	0.10	0.52	149	204	2.0	418	67	0.04	254	7
JER 5124 16	N-1	14.64	0.49	3.14	72.35	0.06	0.54	7.22	0.08	0.46	149	199	1.8	482	62	0.15	265	442
JER 5124 17	N-1	15.62	0.51	3.34	69.94	0.06	0.56	8.38	0.09	0.49	145	215	1.8	567	65	bdl	270	32
JER 5124 20	N-1	14.26	0.51	3.03	72.88	0.05	0.45	7.31	0.07	0.41	118	177	1.6	480	58	bdl	255	24
JER 5124 21	N-1	15.36	0.46	2.97	71.95	0.05	0.57	7.13	0.08	0.41	150	179	1.6	453	61	bdl	260	5
JER 5124 23	N-1	13.47	0.51	3.22	72.14	0.05	0.60	8.53	0.08	0.42	141	199	1.6	581	59	bdl	263	6
JER 5124 24	N-1	15.04	0.49	3.05	71.80	0.05	0.53	7.45	0.09	0.48	173	196	1.9	494	62	bdl	276	283
JER 5124 25	N-1	14.92	0.40	3.01	72.29	0.05	0.57	7.31	0.09	0.43	106	176	1.7	453	68	bdl	258	268
JER 5124 26	N-1	15.16	0.61	2.82	72.05	0.04	0.43	7.42	0.07	0.40	122	173	1.5	464	57	bdl	244	12
JER 5124 27	N-1	14.47	0.65	2.79	70.98	0.17	0.95	8.48	0.10	0.54	327	253	3.6	466	80	0.46	226	23
JER 5124 29	N-1	13.89	0.46	3.26	72.86	0.07	0.77	7.06	0.09	0.45	189	181	1.8	480	67	bdl	271	3
RAM 3592 01	N-1	14.30	0.68	3.19	69.09	0.14	1.09	9.88	0.10	0.56	294	470	4.8	523	73	2.80	265	56
RAM 4740 07	N-1	13.98	0.59	3.28	70.61	0.12	0.71	9.21	0.09	0.51	226	236	3.3	547	68	1.00	244	35
RAM 6297 04	N-1	12.64	0.54	3.27	71.46	0.12	0.52	9.96	0.08	0.48	295	414	4.1	539	57	3.43	278	142
RAM 5947 14	N-1	14.46	0.50	3.50	72.80	0.09	0.51	6.50	0.10	0.68	158	282	2.7	417	64	0.29	254	78
SEP 3791 01	N-1	14.67	0.50	3.02	71.14	0.11	0.60	8.57	0.06	0.38	164	145	0.9	469	45	2.04	241	24
SEP 3791 02	N-1	13.28	0.54	2.99	73.33	0.09	0.50	7.83	0.06	0.44	214	178	0.7	460	46	2.08	230	25
SEP 3791 03	N-1	12.97	0.55	2.85	72.88	0.13	0.56	8.60	0.06	0.39	323	309	1.6	508	49	2.70	230	253
SEP 3791 04	N-1	14.79	0.52	3.06	71.73	0.11	0.66	7.60	0.06	0.39	199	154	0.6	465	46	1.26	233	34
SEP 3791 05	N-1	15.96	0.60	2.99	70.63	0.12	0.79	7.35	0.07	0.43	310	158	0.7	458	58	1.30	220	24
SEP 3791 06	N-1	14.77	0.59	3.16	70.04	0.19	0.67	8.92	0.07	0.50	216	186	0.9	510	50	1.23	248	37
SEP 3791 07	N-1	15.33	0.54	3.26	67.89	0.18	0.66	10.79	0.07	0.49	243	192	0.7	516	53	2.00	234	143
SEP 3791 08	N-1	13.02	0.66	3.45	69.38	0.18	0.57	11.29	0.08	0.53	249	190	0.5	588	60	0.99	337	13
SEP 3791 09	N-1	13.81	0.59	3.27	71.06	0.17	0.56	9.05	0.08	0.45	253	161	0.8	516	54	0.96	234	16
SEP 3791 10	N-1	13.66	0.65	3.37	69.86	0.16	0.59	10.18	0.08	0.51	240	189	1.2	574	59	1.08	306	19
SEP 3791 11	N-1	14.61	0.65	3.02	71.94	0.10	0.55	7.63	0.07	0.41	275	149	0.5	479	57	0.49	231	10
SEP 3791 12	N-1	14.11	0.56	3.30	72.65	0.06	0.48	7.32	0.08	0.48	125	183	0.7	471	59	0.52	249	9
TIB 5583 02	N-1	13.42	0.76	3.47	69.30	0.12	0.50	10.86	0.10	0.57	240	512	3.3	536	69	15.94	271	191
TIB 5583 03	N-1	13.64	0.61	3.42	70.77	0.12	0.74	9.21	0.07	0.44	172	185	1.7	545	48	0.15	273	16
TIB 5583 04	N-1	13.39	0.54	3.38	72.33	0.12	0.85	7.71	0.12	0.58	165	263	2.3	424	69	0.22	263	63
TIB 5583 05	N-1	13.70	0.45	3.37	72.48	0.11	0.62	7.57	0.08	0.47	159	195	1.8	451	54	0.19	264	33
TR 6055 01	N-1	14.08	0.51	3.14	72.60	0.06	0.59	7.59	0.08	0.46	130	196	1.7	492	62	0.05	256	7
TR 6055 03	N-1	14.59	0.64	2.77	70.28	0.16	1.15	8.87	0.08	0.44	283	275	4.5	466	67	1.78	226	50
Bet Eli'ezer																		
JER 5124 18	N-2	11.33	0.56	3.27	73.92	0.10	0.63	8.02	0.11	0.71	147	235	2.5	413	79	6.43	245	6497
NS 6362 02	N-2	11.49	0.59	3.47	73.61	0.11	0.68	7.78	0.10	0.73	140	240	2.4	437	64	7.23	257	7769
AH 3746 01	N-2	11.77	0.37	2.82	75.91	0.10	0.47	7.33	0.05	0.30	232	140	bdl	425	42	5.50	217	5
AH 3746 04	N-2	13.09	0.54	3.31	74.01	0.11	0.65	6.85	0.09	0.52	186	227	bdl	430	62	4.26	229	5
AH 3746 08	N-2	12.04	0.47	3.43	74.39	0.11	0.60	7.70	0.06	0.37	147	189	bdl	457	46	3.53	250	6
AH 3746 12	N-2	10.45	0.43	3.06	73.35	0.14	0.30	10.96	0.08	0.44	228	184	bdl	522	56	3.06	224	8
AH 3746 13	N-2	12.36	0.42	2.90	75.71	0.09	0.49	6.76	0.06	0.38	164	157	bdl	396	40	1.89	225	171
HB 3032 01	N-2	11.48	0.60	3.32	75.45	0.07	0.42	7.25	0.08	0.46	158	185	1.8	477	56	0.07	266	7
JER 5124 07	N-2	13.80	0.46	3.05	73.84	0.06	0.60	6.70	0.09	0.48	166	184	1.8	432	67	0.03	248	6
JER 5124 19	N-2	12.64	0.44	3.22	74.94	0.05	0.60	6.70	0.09	0.45	113	180	1.7	446	64	bdl	272	5
JER 5124 22	N-2	12.51	0.44	3.12	75.35	0.06	0.78	6.36	0.08	0.41	136	171	1.7	454	60	bdl	249	6
JER 5124 30	N-2	12.99	0.46	3.29	75.22	0.06	0.49	5.99	0.11	0.60	106	194	2.2	399	79	bdl	256	6
NS 6362 01	N-2	11.33	0.59	3.28	75.18	0.07	0.53	7.60	0.08	0.46	181	175	1.8	460	54	0.44	263	13
RAM 6490 01	N-2	13.61	0.53	3.48	73.66	0.06	0.53	6.72	0.09	0.55	162	193	2.1	453	64	bdl	265	12
RAM 5947 09	N-2	12.04	0.65	3.41	74.81	0.08	0.40	7.26	0.08	0.45	206	187	1.6	528	54	0.14	259	7
TR 6055 04A[†]	N-2	11.29	0.55	3.55	75.06	0.07	0.46	7.47	0.10	0.55	126	215	2.1	486	66	0.07	275	12
TR 6055 04B[†]	N-2	11.95	0.54	3.51	74.44	0.06	0.39	7.65	0.10	0.55	115	207	2.1	493	63	0.06	277	14
Egypt II																		
AH 3746 02	N-3	13.06	0.52	2.49	72.07	0.11	0.32	8.94	0.27	0.99	175	237	bdl	192	251	5.80	166	2
AH 3746 05	N-3	12.85	0.74	2.83	71.23	0.18	0.62	9.52	0.17	0.76	268	1615	5.3	365	148	77.00	214	307
AH 3746 06	N-3	12.98	0.57	2.77	71.87	0.16	0.28	9.05	0.25	0.92	225	265	bdl	207	219	3.58	172	7
AH 3746 09	N-3	12.31	0.78	3.06	70.25	0.23	0.63	10.63	0.18	0.81	277	1621	5.1	392	165	70.71	227	295
AH 3746 11	N-3	13.46	0.62	2.64	70.41	0.13	0.32	9.72	0.28	1.02	260	2910	8.0	215	254	8.63	190	160
AY 2989 01	N-3	13.65	0.64	2.76	70.50	0.09	0.27	9.55	0.29	1.02	272	208	3.9	230	261	0.01	194	2
AY 2989 02	N-3	15.60	0.60	2.82	68.41	0.11	0.44	9.73	0.20	0.89	237	636	8.5	308	173	6.52	204	1554
AY 2989 03	N-3	13.85	0.72	2.80	70.39	0.10	0.34	9.42	0.27	1.01	343	206	3.8	236	227	bdl	201	3
AY 2989 05	N-3	15.10	0.51	2.62	68.92	0.08	0.25	10.08	0.28	0.93	229	191	3.5	211	257	bdl	186	3
CEA W2S3 03	N-3	13.40	0.57	2.57	70.71	0.08	0.26	9.91	0.29	1.02	318	212	3.8	202	279	bdl	174	4
HB 3032 02	N-3	13.80	0.54	2.40	70.72	0.08	0.36	9.65	0.29	0.95	232	196	3.6	201	287	0.05	174	3
HB 3032 03	N-3	14.67	0.49	2.42	70.49	0.07	0.25	9.20	0.28	0.93	416	189	3.5	199	257	0.08	170	2
HB 3032 05	N-3	14.29	0.54	2.39	70.42	0.07	0.25	9.60	0.29	0.94	232	194	3.5	203	287	0.06	173	2

(*continued*)

Apollonia-type		Major and minor elements as wt %									Selected trace elements as ppm							
		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Fe_2O_3	B_2O_3	MnO	CoO	SrO	ZrO_2	Sb_2O_3	BaO	PbO
HB 3032 10	N-3	14.44	0.76	2.47	70.13	0.08	0.24	9.27	0.27	0.95	335	198	3.7	237	243	0.05	179	2
JER 5124 10	N-3	18.36	0.52	1.88	70.56	0.08	0.30	6.17	0.22	0.69	416	192	2.8	159	129	0.76	131	17
JER 5124 28	N-3 (Mn)	14.67	0.57	2.25	69.34	0.09	0.30	9.29	0.29	0.94	290	9126	5.5	218	282	bdl	243	14
NS 6362 03	N-3	14.72	0.50	2.21	71.42	0.07	0.25	8.71	0.18	0.77	272	155	2.9	184	142	0.19	158	2
NS 6362 05	N-3	14.58	0.44	2.21	70.83	0.06	0.24	9.42	0.24	0.82	213	174	3.1	189	234	0.17	157	2
Egypt II																		
NS 6362 07	N-3	13.52	0.59	2.66	70.76	0.09	0.39	9.48	0.30	1.05	222	273	4.0	209	271	0.10	185	3
NS 6362 08	N-3 (Mn)	14.58	0.58	2.41	68.39	0.11	0.36	9.69	0.28	1.09	245	14426	10.7	215	252	2.08	298	57
NS 6362 09	N-3	14.28	0.52	2.35	70.07	0.09	0.33	10.05	0.28	0.92	166	192	3.4	199	287	0.09	172	3
RAM 4740 01	N-3	12.02	0.68	2.64	72.28	0.11	0.29	9.51	0.29	1.00	300	193	3.4	209	285	0.60	175	5
RAM 4740 03	N-3	12.41	0.88	2.98	70.67	0.13	0.28	10.09	0.33	1.18	390	279	4.4	261	317	0.52	196	64
RAM 4740 09	N-3	14.22	0.49	2.26	69.39	0.09	0.22	10.86	0.28	0.85	274	230	3.2	186	282	0.41	147	19
RAM 4768 01	N-3	13.76	0.51	2.32	71.58	0.09	0.21	9.12	0.27	0.92	240	184	3.3	189	248	2.52	161	3
RAM 4768 02	N-3	13.51	0.51	2.41	71.61	0.09	0.20	9.24	0.27	0.93	243	185	3.3	191	262	2.24	161	3
RAM 4768 03	N-3	13.15	0.58	2.35	71.55	0.11	0.27	9.57	0.28	0.93	283	196	3.4	207	289	3.05	159	398
RAM 4768 07	N-3	13.20	0.49	2.51	72.14	0.07	0.18	8.96	0.24	0.87	111	194	3.2	194	212	1.34	157	4
RAM 5947 01	N-3	14.41	0.47	2.63	68.38	0.08	0.21	11.59	0.23	0.83	142	160	2.8	211	207	0.62	184	4
RAM 5947 02	N-3	12.88	0.53	2.55	72.06	0.09	0.18	9.31	0.27	0.95	300	189	3.1	208	235	0.56	169	7
RAM 5947 04	N-3	14.97	0.44	2.39	72.08	0.07	0.18	7.48	0.26	0.97	323	612	3.7	173	209	0.74	145	38
RAM 5947 05	N-3	15.18	0.46	2.35	70.09	0.09	0.22	9.36	0.24	0.85	421	184	3.0	187	228	0.39	155	6
RAM 5947 07	N-3	14.95	0.52	2.53	69.79	0.09	0.21	9.49	0.27	0.92	220	195	3.3	205	257	0.16	168	6
RAM 5947 08	N-3	14.50	0.52	2.64	69.86	0.09	0.21	9.66	0.29	0.99	204	194	3.4	197	266	0.16	168	6
RAM 5947 10	N-3	14.98	0.55	2.62	69.88	0.10	0.38	9.17	0.25	0.88	221	180	3.1	212	214	0.18	186	6
RAM 5947 11	N-3	14.39	0.52	2.71	70.25	0.09	0.26	9.49	0.28	0.96	233	188	3.2	216	255	0.04	183	2
RAM 5947 12	N-3	13.55	0.41	2.43	69.64	0.08	0.20	11.79	0.19	0.71	246	142	2.3	198	173	0.05	166	3
RAM 5947 13	N-3	14.51	0.55	2.62	70.29	0.10	0.36	9.26	0.25	0.89	211	182	3.1	215	213	0.22	188	5
RAM 5947 15	N-3	13.96	0.50	2.60	71.25	0.08	0.19	9.00	0.27	0.98	297	185	3.1	198	230	0.10	177	4
RAM 5947 16	N-3	14.34	0.49	2.44	71.25	0.10	0.25	8.77	0.26	0.95	338	183	3.6	192	225	1.03	163	7
RAM 5947 18	N-3	12.94	0.56	2.77	71.02	0.09	0.18	9.91	0.30	0.97	268	192	3.3	207	312	1.05	181	4
RAM 5947 19	N-3	13.76	0.52	2.75	70.84	0.09	0.19	9.50	0.25	0.94	222	186	3.2	211	233	0.45	180	6
RAM 5947 21	N-3	16.62	0.54	2.38	68.04	0.11	0.39	9.43	0.28	0.98	232	221	3.2	209	280	0.60	174	9
RAM 5947 23	N-3	14.30	0.52	2.64	70.64	0.08	0.20	9.15	0.27	0.96	301	189	3.2	203	238	0.35	175	8
RAM 5947 24	N-3	15.04	0.35	1.97	70.64	0.07	0.17	9.73	0.17	0.65	350	125	2.1	157	133	0.31	138	6
RAM 5947 25	N-3	14.83	0.51	2.69	69.88	0.10	0.23	9.28	0.28	1.04	227	315	3.7	212	238	0.25	178	25
RAM 6490 02	N-3	13.85	0.41	2.09	70.08	0.07	0.30	11.01	0.21	0.87	431	234	3.0	172	152	bdl	152	4
RAM 6490 03	N-3	13.11	0.72	2.66	70.82	0.09	0.36	9.77	0.30	1.03	315	255	4.4	225	296	bdl	189	4
RAM 6490 04	N-3	15.60	0.49	2.46	69.66	0.07	0.26	9.17	0.26	0.93	229	196	3.6	196	241	bdl	169	3
Egypt II																		
RAM 6490 10	N-3	15.82	0.58	2.68	68.99	0.07	0.27	8.98	0.28	1.04	257	216	4.1	209	236	bdl	184	3
RAM 5947 20	N-3	12.50	1.78	2.01	70.52	0.21	0.98	9.90	0.19	0.79	295	1107	12.2	398	206	4.49	162	337
RAM 5947 06	N-3	15.02	0.63	2.93	68.66	0.12	0.37	9.98	0.23	0.89	267	798	6.8	302	211	8.39	205	1222
RAM 3592 03	N-3 (Co)	13.65	0.75	2.73	68.66	0.13	0.41	10.09	0.29	1.53	312	3191	436.9	247	263	2.86	226	532
RAM 6297 06	N-3 (Co)	14.04	0.73	2.71	68.89	0.10	0.40	9.75	0.28	1.45	278	3379	588.7	229	257	0.62	210	92
TIB 5583 06	N-3 (Co)	15.21	0.53	2.54	68.44	0.11	0.31	9.65	0.26	1.28	360	2345	742.4	207	220	1.66	180	82
Egypt I																		
AH 3746 10	N-4	16.07	0.81	4.38	72.13	0.11	0.42	2.67	0.55	1.81	204	398	1.5	214	245	2.49	216	7
TIB 5583 01	N-4	18.06	0.86	4.53	69.75	0.05	0.43	2.76	0.54	1.76	278	412	7.0	224	265	0.13	242	4
Outlier																		
AH 3746 03	Outlier	13.40	0.58	2.67	70.76	0.16	0.50	8.49	0.13	1.13	385	3596	15.7	390	109	2116.57	220	4484
NS 6362 04	Outlier	15.30	0.72	3.28	68.46	0.13	0.55	9.45	0.14	0.88	207	685	8.5	418	94	13.47	230	1635
NS 6362 10	Outlier	14.54	0.67	3.38	70.60	0.09	0.47	8.20	0.17	0.91	198	306	5.4	372	107	5.15	221	1349
RAM 5947 22	Outlier	15.80	0.66	2.80	68.01	0.15	0.52	9.40	0.18	0.89	255	1735	17.7	375	152	24.74	233	3311
RAM 5947 03	Outlier	15.59	0.59	3.38	69.73	0.11	0.32	7.93	0.19	0.95	211	613	7.2	347	132	3.87	214	527

† analysis A of vessel body, analysis B of trailed decoration, bdl = below detection limit, n/a = data not available.

Appendices B-D. Supplementary data

Supplementary data containing Appendices B-D and also additional trace elemental data for Appendix A can be found at https://dx.doi.org/10.1016/j.jas.2016.08.006.

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