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CHARACTERIZATION AND PROVENANCE OF LATE ANTIQUE WINDOW GLASS FROM THE PETRA CHURCH IN JORDAN*

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Fifth- to seventh-century window glass fragments from the Petra Church in Jordan were analysed by EPMA and spectrophotometry to characterize their optical properties and chemical composition. The objective of this study was to determine the provenance of the raw glass and the secondary production procedures of the window-panes. Judging from the material evidence, both the crown window-panes and possibly the rectangular samples were produced through glass-blowing techniques. The chemical data show that the assemblage forms a homogeneous group of soda–lime–silica glass of the Levantine I type. The green glass, however, has higher silica and lower soda contents than the aqua-blue fragments. The composition of one sample suggested the recycling of Roman glass. Our results confirm the trade of glass between the Levantine coast and Petra during Late Antiquity. No colouring agents other than iron were detected. Spectrophotometry confirmed the presence of iron and showed that the window fragments absorbed light relatively equally across the visible part of the spectrum. The windows thus seem to have provided an almost colourless illumination for the sacred interior.

KEYWORDS: LATE ANTIQUITY, BYZANTINE, WINDOW GLASS, WINDOW-PANES, PETRA, JORDAN, PRINCIPAL COMPONENT ANALYSIS, SPECTROPHOTOMETRY, ELECTRON MICROPROBE, LEVANTINE I GLASS

INTRODUCTION

The ancient city of Petra is located in southwestern Jordan, within the eastern rim of the Jordan Dead Sea Transform, about halfway between the Dead Sea and the Gulf of ‘Aqaba. Once capital of the Nabataean Kingdom, Petra remained an important urban and political centre during the Roman and early Byzantine periods. Many of the carbonized documents recovered from the Petra Church during excavations in 1993 suggest that Petra was a significant regional administrative centre of the Byzantine Empire, and that it was still fully functional in the middle of the sixth century (Bikai and Egan 1996; Egan and Bikai 1998).

The Petra Church represents one of the larger ecclesiastical complexes in Petra and construction of the church probably began in the late fifth century. The church was gradually destroyed first by fire, presumably towards the end of the sixth or the beginning of the seventh century, and subsequently by earthquakes in the seventh century. Accumulation due to natural

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phenomena and post-ecclesiastical occupation of the complex resulted in substantial re-deposition of various materials within the site (Fiema 2001).

Three major excavation campaigns at the Petra Church complex were carried out between May 1992 and July 1996 (Fiema and Schick 2001). These excavations yielded a multitude of glass fragments of vessels and windows, glass paste cakes and mosaic tesserae, some of which have been described and discussed in terms of typology and chemical composition (Marii 2001; O'Hea 2001). The major aim of this paper is to characterize the chemical composition and manufacturing techniques of the window glass recovered from the Petra Church, as well as to compare these results to glass groups prevalent in Late Antiquity in order to determine the provenance of the raw glass. The systematic description and chemical characterization of the window glass fragments can reveal important differences as regards chronological and geographical factors in the manufacture of glass in Late Antiquity.

MATERIALS

Twenty-three window glass fragments were chosen for analysis, all deriving from the three excavation campaigns at the Petra Church (1992, 1994 and 1996) and found at various places throughout the building. Most of the fragments were covered with a layer of flaky iridescence or milky weathering with patches of iridescent film. Fragments were chosen on the basis of signs related to the secondary production process. The selected samples had either retained part of their edges or were clearly identifiable crown panes, and they covered the entire array of aqua-colours from transparent to translucent aqua-blue, yellowish-green and dark bottle green. These samples were thus representative for the range of window glass extant (Table 1). According to the stratigraphic sequence, the glass can be attributed to the period between the fifth and the seventh centuries (Fiema 2001). However, it cannot be ruled out that some earlier glass might have been recycled or reused from either previous structures on the site or other nearby edifices. The destruction of the church by fire at the end of the sixth or beginning of the seventh century seems likely to be the *terminus post quem* for the assemblage.

METHODOLOGY

Sampling

For electron probe microanalysis (EPMA), small sections, typically of a few millimetres, were taken from the window fragments with a diamond-coated circular-bladed saw. The fragments were embedded in epoxy resin, ground and polished in cross-section on successive grades down to 0.25 μm. The polished blocks were vacuum carbon coated to ensure electrical conductivity and thus prevent surface charging during analysis.

Analytical techniques

To establish the major and minor element composition of the samples, an electron probe microanalysis (EPMA) was carried out, using a JEOL JXA-8600 superprobe with a wavelength-dispersive spectrometer (WDS). The operating conditions were a 15 keV accelerating potential, a 60 nA incident beam current and a take-off angle of 40°. The concentrations of 21 elements (Na, K, Mg, Ca, Ba, Ti, Cr, Mn, Fe, Co, Cu, Zn, Al, Si, Sn, Pb, P, As, Sb, S and Cl) were measured and calculated as weight percent (wt%) oxide values using a ZAF correction procedure (Table 2).

Table 1 *Summary of material characteristics of the window-panes. The sample's name consists of the abbreviation 'PCP' for 'Petra Church Project', the year of its recovery and a running number assigned by the author; the locus corresponds to the archaeological context of the sample (Fiema 2001)*

Sample	*Locus*	*Type*	*Colour*	*Thickness (mm)*	*Edges*	*Surface structure*	*Bubbles*
PCP-92-001	G2.12	Rectangular	Aqua-blue, translucent	2.8–3.6	Grozed	One smooth, one grooves	Pronounced elongated, various sizes
PCP-92-002	F4.20	Rectangular	Aqua-blue, transparent	1.3–2.9	Raised rim	Smooth inside, possibly grooves on the outside	Very few round, small
PCP-96-003	M3.07	Round	Olive green, translucent	0.8–4.5	Missing	Both smooth	Very few spherical
PCP-94-004	C4.04	Rectangular	Aqua-blue, translucent	2.0–2.3	Rounded	One smooth, one slightly rougher	Few spherical, various sizes, randomly distributed
PCP-94-005	L1.03	Rectangular	Aqua-blue, translucent	3.3–4.3	Grozed	One smooth, one tendency of grooves	Few, some slightly elongated, some rounded, various sizes
PCP-96-006	C4.06	Rectangular	Aqua-blue, translucent	4.2–5.3	Grozed	One smooth, one pronounced grooves	Very small and few, round
PCP-92-007	B2.13	Rectangular	Aqua-blue, translucent	2.3–5.0	Grozed and rounded	Both smooth	Very few small, spherical, occasional bigger ones
PCP-93-008	IIIB.05	Rectangular	Aqua-blue, translucent	2.3–3.2	Grozed and possibly cut	Possibly smooth	Few elongated, various sizes, some are huge
PCP-93-009	I.12A	Rectangular	Dark bottle green, translucent	3.0–4.2	Rounded	Badly burnt	Very few, spherical of various sizes
PCP-92-010	G2.10	Rectangular	Aqua-blue, possibly transparent	3.9–4.5	Rounded	One smooth, one pronounced grooves	Few round
PCP-96-011	M3.05	Round	Dark bottle green, translucent	4.7–9.8	Missing	Both smooth	Few round of various sizes
PCP-92-012	F4.14	Rectangular	Aqua-blue, translucent	2.3–3.2	Grozed	One smooth, one slight grooves	Few mostly round, some elongated, various sizes, along the grooves

Table 1 *(continued)*

Sample	*Locus*	*Type*	*Colour*	*Thickness (mm)*	*Edges*	*Surface structure*	*Bubbles*
PCP-93-013	I.07	Round	Aqua-blue, translucent	3.0–3.8	Missing	Both smooth	Few round various sizes
PCP-92-014	B1.03	Rectangular	Dark bottle green, translucent	5.5–6.4	Grozed	One smooth, one grooves	Few slightly elongated
PCP-92-015	B1.03	Rectangular	Aqua-blue to colourless, transparent	2.4–2.5	Grozed	Both very smooth	Few elongated, varying in size
PCP-94-016	C4.06	Rectangular	Aqua-blue, translucent	3.6–5.3	Grozed	One very smooth, one pronounced grooves	Few spherical, randomly distributed
PCP-92-017	B1.18	Rectangular	Aqua-blue, translucent	3.2–4.2	Grozed and possibly rounded	Both relatively smooth	Very few spherical
PCP-94-018	L2.05	Rectangular	Aqua-blue, translucent	4.0–5.2	Rounded	One smooth, one pronounced grooves	Few round and elongated of different sizes
PCP-94-019	L2.05	Rectangular	Aqua-blue, translucent	4.0–5.0	Rounded	One possibly smooth, one pronounced grooves	Few, some are distinctly elongated
PCP-93-020	A3.16	Round	n.d.	3.5	Folded	Badly corroded	n.d.
PCP-93-021	H1.05	Round	Aqua-blue, translucent	3.2	Folded	Smooth	Elongated along the circumference
PCP-92-022	F2.22	Round	Virtually colourless, transparent	2.8	Folded	Smooth	Elongated along the circumference
PCP-92-023	F2.03	Round	Light olive green, translucent	2.3	Folded	Smooth	Very few elongated along the circumference

Table 2 *Means of the normalized results from the EPMA analysis (in %). Multiple measurements (*n ≥ *10) for each sample (typically between 98.2 wt% and 100.7 wt%) were normalized and then averaged*

Sample	SiO_2	Al_2O_3	Fe_2O_3	*CaO*	*MgO*	Na_2O	K_2O	TiO_2	*MnO*	P_2O_5	SO_3	*Cl*
PCP-92-001	69.69	2.95	0.50	9.17	0.54	15.13	0.88	0.07		0.14	0.14	0.73
PCP-92-002	70.42	2.25	0.41	7.52	0.38	16.21	0.58	0.07	0.80	0.15	0.21	0.99
PCP-96-003	71.98	2.68	0.44	8.24	0.56	13.99	1.00	0.08		0.14		0.87
PCP-94-004	71.14	2.85	0.39	8.30	0.44	14.98	0.73	0.07			0.16	0.87
PCP-94-005	69.55	3.01	0.53	9.47	0.49	14.88	0.91	0.10		0.14	0.18	0.74
PCP-96-006	69.16	2.97	0.51	9.30	0.54	15.54	0.75	0.08		0.11	0.20	0.83
PCP-92-007	70.11	2.93	0.50	9.14	0.50	14.89	0.89	0.09		0.13	0.13	0.68
PCP-92-008	69.23	3.03	0.54	9.48	0.54	15.13	0.89	0.08		0.13	0.20	0.75
PCP-93-009	66.64	2.84	0.64	10.98	0.63	15.13	1.78	0.11	0.15	0.34	0.12	0.63
PCP-92-010	68.36	2.91	0.48	10.21	0.50	15.60	0.8	0.09		0.11	0.21	0.73
PCP-96-011	70.83	2.83	0.56	9.14	0.63	13.53	1.4	0.10		0.21		0.72
PCP-92-012	69.83	2.96	0.50	9.07	0.53	15.14	0.85	0.09		0.15	0.14	0.72
PCP-93-013	67.64	2.78	0.57	10.06	0.60	15.45	1.53	0.11	0.16	0.29	0.12	0.69
PCP-92-014	71.61	2.92	0.51	9.02	0.48	13.40	1.15	0.10		0.15		0.67
PCP-92-015	70.17	2.88	0.52	9.33	0.60	14.50	0.91	0.10	0.11	0.15		0.68
PCP-94-016	69.03	2.96	0.46	9.27	0.56	15.74	0.75	0.10		0.10	0.21	0.82
PCP-92-017	68.34	2.72	0.50	9.18	0.56	16.11	1.22	0.09	0.17	0.21	0.13	0.76
PCP-94-018	70.96	2.86	0.40	8.41	0.43	15.01	0.73	0.07		0.10	0.17	0.87
PCP-94-019	70.91	2.87	0.42	8.67	0.45	14.74	0.78	0.08		0.10	0.15	0.84
PCP-93-020	69.48	2.86	0.43	9.08	0.41	15.98	0.67	0.09			0.14	0.78
PCP-93-021	69.47	2.90	0.43	9.05	0.42	15.99	0.65	0.08		0.09	0.16	0.75
PCP-92-022	69.43	3.06	0.62	9.59	0.66	14.56	1.03	0.11		0.15	0.08	0.68
PCP-92-023	71.57	2.68	0.47	8.47	0.52	14.19	1.01	0.08		0.15		0.86
Average	69.81	2.86	0.49	9.14	0.52	15.04	0.95	0.09		0.15	0.16	0.77
Standard deviation (σ)	1.31	0.17	0.07	0.72	0.08	0.77	0.29	0.01		0.06	0.04	0.09
Relative σ	1.88	5.82	13.50	7.83	14.6	5.12	30.97	14.94		41.71	23.66	11.37

The detection limit for P_2O_5 was about 0.085%, for TiO_2 about 0.06% and for SO_3 about 0.07%. For all other compounds, values below 0.1% were unreliable and thus not taken into account. The composition of each sample represents the mean of at least 10 area analyses ($n \geq 10$) that were taken from different areas across the cross-section of the polished specimen. The absolute standard deviation (σ) and the relative standard deviations (σ/average) of the individual measurements were calculated in order to ascertain the consistency and homogeneity of the assemblage (Table 2). For comparison with published compositional data sets, the Corning glass standards A and B were used to evaluate the accuracy of the analysis and correct the data.

For X-ray fluorescence analysis, a sequential energy-dispersive Spectro 2000 ED-XRF equipment (Tq-0261 method) was used. This analysis served to qualitatively identify components of low concentration that cannot be easily detected by electron probe microanalysis due to limitations in the detection limits. Three ED-XRF measurements were performed on each specimen with a live time set at 150 s and three different polarizing targets. The qualitative results of all major, minor and trace elements of 50 ppm or more were calculated stoichiometrically as oxides and normalized to 100%. In contrast to EPMA, the accuracy of the ED-XRF data was low, showing relative differences of around 25% between the measured and the certified

values for soda and silica in the two glass standards analysed and even higher variance for alumina. This reflects the lack of sample preparation for ED-XRF analysis, and resulting problems with surface morphology and alteration.

To gain insights into how the window glasses from Petra obtained their different colours, optical absorbance spectra were measured using a Cary 50 spectrophotometer, version 3.0. The instrument operates on a dual-beam mode, using a full-spectrum tungsten light source and measuring in the wavelength range of 200–800 nm. The baseline was calibrated against air and the measurements were thus adjusted. The accuracy of the instrument was initially checked against a modern microscopic glass slide. Since no sample preparation was possible for the archaeological glasses, the absorbance spectra of the unmodified glass fragments were measured. To compensate at least partially for the surface condition of the specimens, repeated measurements ($n \geq 3$) were performed and the average of these calculated. Measurements that were clearly affected by the corrosion layer were ignored. Furthermore, the thickness of the samples was determined as accurately as possible and individual spectra were normalized to a path length of 1 mm for comparison. The absorption was then plotted against the wavelength (in nm) according to the formula:

$$A_\lambda = \log \frac{I_o}{I}$$

where A_λ is the absorbance at a given wavelength λ, I_o is the initial light intensity emitted from the light source and I is the amount of transmitted light (see Fig. 2 below).

Data analysis/statistical methods

To identify and explain group structures, principal component analysis (PCA) was performed on the EPMA data of the major and minor elements using a SPSS 11 program (for Mac OSX). To minimize the errors inevitably caused by the difference in concentration between the major and minor elements, the data were initially subjected to autoscaling (or z-transform). PCA was carried out on the matrix of correlation coefficients of each of the seven variables (SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O and K_2O) with every other variable. The relationships between the most expressive principal components (PC) as defined by an *Eigenvalue* > 1 was then determined on the basis of simple bivariate plots (Shennan 1997). For comparison of the Petra Church samples with glass reference groups, the Petra compositional data were adjusted according to the Corning glass standards prior to PCA. A small correction of +6% relative was applied to the measured Al_2O_3 values, Fe_2O_3 levels were adjusted by +7% and MgO by +12.5% relative. The Na_2O, SiO_2 and K_2O values were adjusted by −2%, −1% and −1% relative, respectively.

RESULTS AND DISCUSSION

Composition of the Petra Church glass samples

All of the 23 analysed window glass samples can be classified as soda–lime–silica glasses (Table 2), with average silica contents of about 70% (SiO_2), about 15% soda (Na_2O) and approximately 9% lime (CaO). The relative standard deviations between the samples are less than 2% for silica and between 5% and 8% for the other main compounds, exemplifying that the window glass fragments under investigation form an exceedingly homogeneous group.

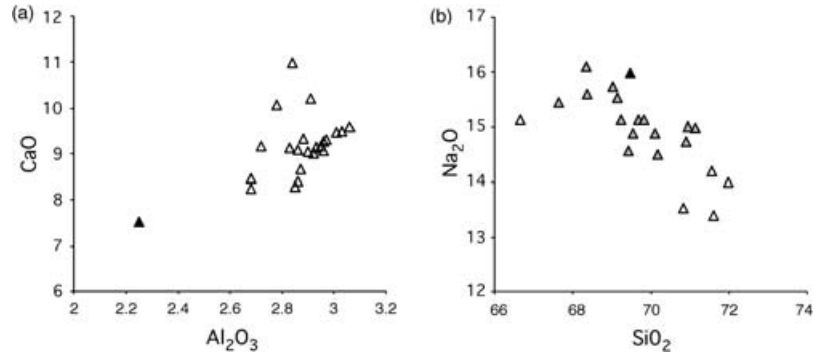

Figure 1 *The group structure of the Petra Church window glass. (a) Calcium versus aluminium concentrations of the 23 glass fragments. Sample 002 is indicated in black. (b) Soda versus silica levels of the 23 glass fragments; aqua-blue samples indicated in grey, green samples in white and sample 002 in black. Note that the green samples (with the exception of sample 009) have higher silica and lower soda levels than the aqua-blue fragments.*

Judging from the low magnesium and potassium concentrations of the window glass fragments (average MgO and K_2O < 1 wt%), mineral soda (natron) was most certainly used for their production (Freestone *et al*. 2003). The samples typically show low concentrations also for iron (average Fe_2O_3 < 0.5 wt%), which indicates a relatively high purity of the raw materials employed.

A comparison of aluminium and calcium concentrations confirms the homogeneity of the assemblage, with values in the range of 3% and 9%, respectively (Fig. 1 (a)). The correlation of alumina concentrations with the calcium contents is particularly indicative of variations in the silica sources (Freestone *et al*. 2000, 2002b; Tal *et al*. 2004). The narrow distribution of 22 of the Petra Church fragments is therefore compatible with the use of a common silica source. Only sample 002 is a clear outlier with distinctly lower alumina and lime concentrations.

It has been proposed that the silica and soda levels of glass samples may be correlated to the secondary manufacturing process, with higher soda and lower silica concentrations associated with cast samples as compared to blown fragments (Fischer and McCray 1999). As a consequence, the glass has a higher fluidity and is thus more suitable to pouring and casting. However, no obvious compositional differences between the types of window-panes in the Petra Church assemblage could be observed (see the section on the secondary manufacturing process below). As mentioned above, both silica and soda levels are relatively equal across the 23 samples (Table 2) and appear to vary independently of whether it is a round (e.g., 003 and 013) or rectangular (e.g., 014 and 006) window-pane (Table 1). There seems to be a tendency, however, that green glasses have slightly less soda and more silica than aqua-blue fragments, with the exception of sample 009. This could potentially indicate a separation between the manufacture of aqua-blue and green glasses, and suggests that they differ in their melting temperatures (Fig. 1 (b)).

Colouring agents

No significant amounts of colouring or opacifying agents other than iron could generally be detected in the Petra Church samples. As judged by ED-XRF analysis (data not shown), cobalt concentrations are typically around 10 ppm and copper ranges from 12 to 70 ppm. Sample 023

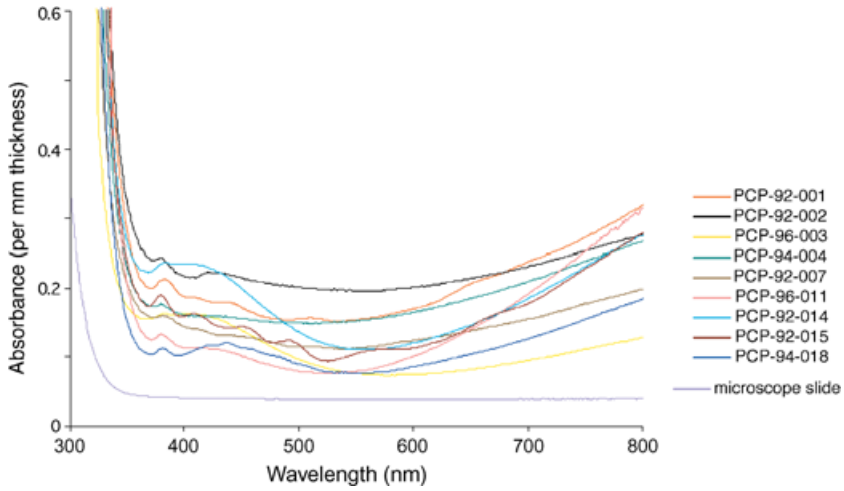

Figure 2 *The optical absorbance spectra of nine window glass fragments in the wavelength range of 300–800 nm, normalized to a sample thickness of 1 mm.*

shows an unusually high lead content (1444 ppm), which, however, could not be verified by means of EPMA. Sample 002 is outstanding insofar as it has significantly higher levels of manganese (4980 ppm) and antimony (346 ppm) than any of the other samples (typically < 500 ppm manganese and < 10 ppm antimony). This finding is confirmed by the EPMA data (Table 2). Taken together, it seems that no colouring agents were deliberately added to the glass batch. The presence of iron at concentrations of about 0.5% can be explained by the naturally occurring iron in the raw materials, particularly the silica source, rather than the intentional addition of iron (Fiori and Vandini 2004).

The absence of colouring or opacifying agents is also confirmed by photometric analysis of nine samples (Fig. 2). None of the typical transition metal absorption bands could be observed, such as that of Mn^{3+} (λ_{max} = 470–520 nm) or Co^{2+} (λ_{max} at 530, 585 and 647 nm) (Weyl 1976; Green and Hart 1987). However, in accordance with the compositional data a sharp peak at about 380 nm could be identified in all nine measured samples that is usually attributed to the presence of iron in the oxidation state Fe^{3+} (Green and Hart 1987; Glebov and Boulos 1998). Samples 001 and 015 show a further distinct absorption peak at about 415 nm and several samples have a peak at about 440 nm, corresponding to known absorption bands of the ferric ion Fe^{3+}. On their own, these absorption bands give a very pale lemon yellow colour. However, it is likely that the ferrous ion Fe^{2+} with an absorption band centred on a wavelength of 1075 nm and extending into the visible part of the spectrum is simultaneously present in the glass, affecting the light absorption in the red region (Glebov and Boulos 1998). Indeed, some samples (e.g., 002, 007 and 018) exhibit further absorption maxima at a wavelength of around 420 nm, which is a known absorption band of the ferrous ion Fe^{2+} (Glebov and Boulos 1998). In conjunction, these bands impart a greenish-bluish tint to the glass (Green and Hart 1987). This seems to be true for all the analysed glass samples, with the exception of sample 003, which expresses a yellowish-green colour. This could possibly indicate a different ratio of divalent and trivalent iron ions in this particular glass sample with a bias for Fe^{3+}. This is also reflected in the spectrum of this sample, with increased absorption in the blue range relative to the rest of the visible spectrum.

It can thus be postulated that the main colouring agent of the Petra Church window glass seems to be iron in both Fe^{2+} and Fe^{3+} states of oxidation. This could mean that the window glass was produced with the highest possible transmission of light in mind to provide an efficacious level of luminance for the ecclesiastical space.

Provenance of the Petra Church glass

It has been shown that the composition of the window glass from the Petra Church corresponds to typical soda–lime–silica glass that was prevalent in the first half of the first millennium CE. Of the different glass types identified in the central and eastern Mediterranean for the period in question (Fiori and Vandini 2004), the chemical composition of Levantine glass seems to resemble that of the Petra Church assemblage most closely. The data from the Petra Church were thus compared with published data from the so-called Levantine I and Levantine II glass groups.

Levantine I glass was originally defined by Freestone and colleagues and comprises sixth- to seventh-century glass from Dor and Apollonia (Freestone *et al*. 2000), and fourth-century glass from Jalame (Brill 1988). Evidence strongly suggests that the renowned sand from the Belus delta in the Bay of Haifa or similar coastal sands containing calcareous fragments were used for the production of Levantine I glass (Freestone *et al*. 2003). This type of glass is similar to the European Roman glass, but nonetheless differs in that it is slightly higher in lime (CaO around 8–9%, as compared to 6.5–7.5% in Roman glass) and higher in alumina (Al_2O_3 of about 2.5–3%, as compared to 2–2.5%) (Freestone *et al*. 2000). The Levantine II category is associated with the large-scale glass manufacture installations at Bet Eli'ezer, near Hadera in Israel, which seems to have been active between the sixth and the early eighth centuries (Freestone *et al*. 2002a, 2003; Freestone 2003). The glass is distinct from Levantine I and European Roman glass for its lower lime and sodium and concurrently higher silica concentrations, indicating a different silica source than the one utilized for Levantine I glass, but still some local coastal sand (Freestone and Gorin-Rosen 1999; Freestone *et al*. 2002a, 2003).

A principal component analysis was carried out, including the data sets from the Petra Church and Levantine I and II glass to identify possible overlaps, while taking into account the multidimensional group structures. For this comparison, the Petra Church data were corrected in line with the measurements of Corning glass standards (see methods). The principal component analysis was then performed on the transformed data for the compounds Al_2O_3, CaO, FeO, MgO, Na_2O, SiO_2 and K_2O.

The first three principal components (PC) account for almost 84% of the total variation and are sufficient to delineate the individual groups (Table 3). The first two components comprise about 72.5% of the entire variance and distinguish plainly between Levantine I and Levantine II glass (Fig. 3 (a)). In this analysis, the Petra Church samples fall clearly within the range of the Levantine I glass. The comparison of PC1 with PC3, accounting for 61% of the total variance, confirms the overlap of the Petra Church samples with the Levantine I reference group (Fig. 3 (b)). The loading scores of the component matrix (Table 4) indicate that Levantine I glass as well as the Petra Church window glass vary from Levantine II glass in that it contains typically more CaO, Na_2O and K_2O and less SiO_2 and Al_2O_3. Principal component PC1 versus PC3 furthermore identifies a subgroup of the Levantine I specimens with seemingly elevated levels of magnesium, associated with PC3. Since PC3 has an *Eigenvalue* < 1 and accounts for only about 11% of the variance, this subgroup is of no great relevance and is not clearly isolated in a dendrogram of the de-normalized seven principal component scores either (data not shown).

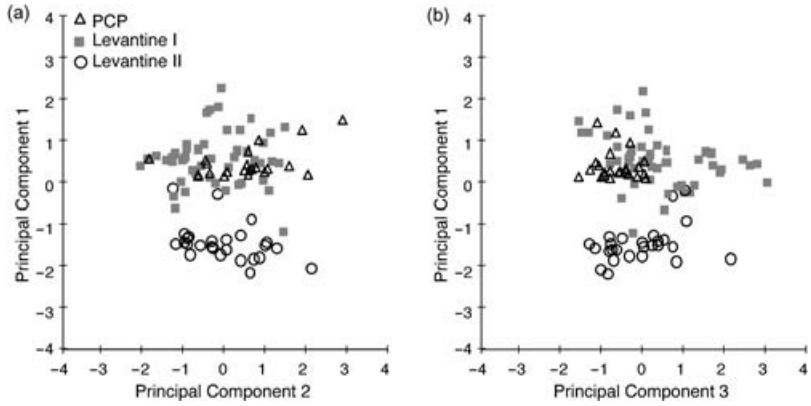

Figure 3 *PCA of Petra Church and Levantine glass. (a) PC1 versus PC2 for the Petra Church window fragments compared with data sets from Levantine I glass from Jalame (Brill 1988), Apollonia and Dor (Freestone* et al. *2000) and Levantine II data from the Bet Eli'ezer furnaces (Freestone* et al. *2002a, 2003; Freestone 2003). (b) PC1 versus PC3 for the same glass assemblages.*

Table 3 Eigenvalues *and variance accounted for by the seven principal components of the chemical compositions of Levantine I and II and Petra Church data*

Principal component	Eigenvalues	*% of variance*	*Cumulative %*
1	3.476	49.659	49.659
2	1.602	22.883	72.543
3	0.790	11.279	83.821
4	0.479	6.843	90.665
5	0.433	6.180	96.845
6	0.201	2.868	99.713
7	0.020	0.287	100.000

Table 4 *Component matrix containing the loading scores of the PCA of Levantine I and II and the Petra Church data*

Component	*1*	*2*	*3*
Al_2O_3	–0.635	0.513	–0.378
CaO	0.791	0.402	–0.097
FeO	–0.491	0.715	–0.141
MgO	–0.208	0.648	0.716
Na_2O	0.870	–0.084	0.177
SiO_2	–0.921	–0.306	0.042
K_2O	0.746	0.382	–0.269

The comparison of these data sets provides ample evidence that the glass employed for the Late Antique windows in the Petra Church in Jordan is closely related to Levantine I glass from fourth-century Jalame and sixth- to seventh-century glass from Dor and Apollonia. It thus seems feasible to assume that these different sites relied on the same raw glass, supplied possibly

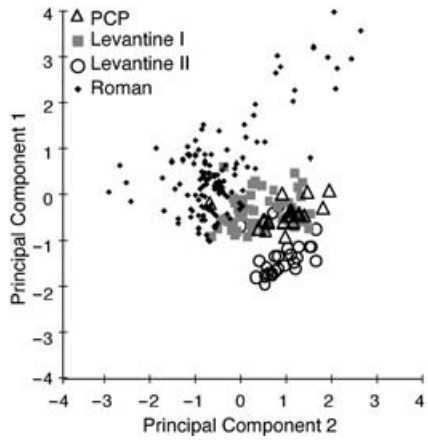

Figure 4 *PCA including Roman glass samples. PC1 is plotted against PC2, comparing data from the Petra Church, Levantine I glass from Jalame (Brill 1988), Apollonia and Dor (Freestone* et al. *2000), Levantine II data from the Bet Eli'ezer furnaces (Freestone* et al. *2002a, 2003; Freestone 2003) and Roman glass from Augusta Praetoria (Mirti* et al. *1993) and Emilia Romagna (Arletti* et al. *2005).*

by the same primary glass manufacturing factories. Following the extensive investigation of the Jalame glass and its potential raw materials (Brill 1988), it is likely that the glass used at Petra derived ultimately from the Palestinian coast.

Since some of the Petra Church window glass fragments do not fully coincide with the main Levantine I group and since Levantine I glass resembles European Roman glass relatively closely, the principal component analysis was extended to include two Roman data sets from mainland Italy. The chemical compositions of glass from Augusta Praetoria (Aosta, first to fourth centuries CE) (Mirti *et al*. 1993) and of contemporary glass from western Emilia Romagna (first to fourth/fifth centuries CE) (Arletti *et al*. 2005) were added to the principal component analysis, designated as 'Roman'. Only data of non-coloured glass fragments was included in the procedure, to avoid distortions due to possible colouring agents. Also, the Augusta Praetoria sample 04 was removed from the data set, since it has exceptionally high values in CaO (> 10%) and K_2O (almost 8%) and low levels of Na_2O (< 10%).

The first two principal components have *Eigenvalues* > 1 and account for about 60% of the total variance, with PC1 covering about 35% and PC2 25%. PC1 and PC2 enable the distinction between the three different glass reference groups—Levantine I, Levantine II and Roman (Fig. 4)—with the Roman data not forming a narrow cluster, but distributing into subgroups. All but one of the Petra Church specimens are unambiguously associated with Levantine I. Interestingly, sample 002 coincides clearly with the main Roman cluster. This sample had previously proven exceptional within the Petra Church assemblage, due to its relatively low concentrations of alumina and calcium oxide and high levels of manganese and antimony. This sample is furthermore distinct from the rest of the assemblage in that it is the only specimen with a raised rim (Fig. 5 (a)). It thus seems likely that sample 002 is an older, possibly Roman glass that was recycled.

Levantine I and the Petra Church glass differs from the Roman samples mainly in that they have higher Al_2O_3, CaO and marginally higher K_2O, and lower Na_2O, concentrations. These results are at large in agreement with previous findings by Freestone *et al*. (2000) as to the

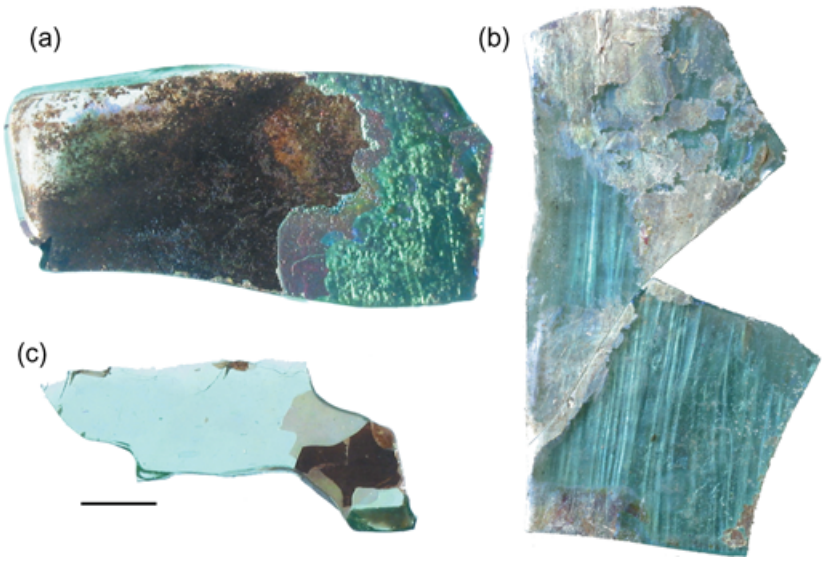

Figure 5 *Representative window glass fragments: (a) sample 002, an aqua-blue fragment of a rectangular window-pane with a raised rim; (b) sample 018, a fragment of a large rectangular window-pane with a straight rounded edge—one side is smooth, while the other side exhibits pronounced parallel grooves; (c) sample 015, a non-coloured, delicate fragment of a rectangular window-pane with a grozed edge and two smooth surfaces. Scale bar: 2 cm (b) and 1 cm (a, c).*

differences between Roman and Levantine I glass. Following these observations, it can be concluded that the window glass from the Petra Church in Jordan derived primarily from a Levantine I source. Nonetheless, at least one of the glass samples (002) seems to have a close affinity with Roman glass-making traditions, potentially indicating the recycling of Roman glass or even the reuse of whole window-panes as spolia. The use of spolia is well attested in Petra (Fiema 2001) and the reuse specifically of window glass seems to be very likely (Price 1996). A comparison with contemporary glass from the nearby North Ridge Church and the more ancient glass fragments from the Great Temple at Petra seems to further support the hypothesis that there was a change in the supply of glass at Petra some time between the fourth and the seventh century (Swan 2004; Schibille 2005; Marii 2007).

Secondary manufacturing process

Thus far the analysed window glass assemblage from the Petra Church has proven remarkably homogeneous with respect to its chemical and optical parameters (with the exception of sample 002). This would seem to indicate that the material originates from a single primary production site. The material characteristics of the fragments, on the other hand, suggest at least two secondary manufacturing procedures for the window-panes.

Three different techniques of secondary window glass production are known: the cast and/or roller-moulded type of plate glass, the muff or cylinder-blown sheet glass and the crown or bull's eye glass (Harden 1939, 1959; Haevernick and Hahn-Weinheimer 1955; Boon 1966; Baatz 1991). Casting seems to have been the prevailing technique during the Roman period

up to the third century. From around 300 CE, the cylinder-blown window sheets seem to have become more widespread and initially existed alongside the older casting technique (Boon 1966; Price 1996).

The experimental reproduction of the casting procedure has resulted in glass panes resembling Roman artefacts (Taylor 2001; Allen 2002). The distinction between the cylinder-blowing technique and casting on the basis of their material characteristics is nonetheless ambiguous, not least because both processes produce rectangular or square window-panes. Attributes such as the surface condition, the thickness of the glass and the shape and orientation of the air bubbles within the glass fabric are believed to distinguish between the cast plate glass and the cylinder-blown sheet (Haevernick and Hahn-Weinheimer 1955; Harden 1959; Boon 1966; Baatz 1991; Price 1996; Kessler *et al*. 2005; Wolf *et al*. 2005). However, there is some disagreement as to the conclusiveness of these material features (Haevernick and Hahn-Weinheimer 1955; Harden 1959; Schuler 1959; Boon 1966; Braun 1983).

In contrast, crown glass is easy to identify. Crown glass was made by blowing a spherical shape, which was then attached to a pontil and knocked off the blowpipe. The globe was opened out and spun to flatten the glass into a disc or wheel-like shape by centrifugal force. As a result, the round pane is usually thick at its centre and significantly thinner towards the edges. The crown glass can furthermore be recognized by the 'bullion' in the centre where the pontil was attached and, if air bubbles or impurities are present in the glass, these would more often than not be spread in a spiral formation. For the purpose of strengthening the rim, the edges of the glass disc are sometimes folded over (Harden 1959; Meyer 1988).

The majority of window-panes from the Petra Church seem to have been rectangular, for only seven out of the 23 fragments unmistakably come from round crown window-panes. It has been proposed that the round panes were reserved for certain areas, possibly the clerestory windows (O'Hea 2001). Some of the circular window fragments discussed here were indeed recovered from the eastern end of the nave, but also from the southern subsidiary apse, while the other three crown panes presumably derive from secondary deposits associated with post-ecclesiastical collection points (Table 1).

Only one window-pane (sample 002) has a raised rim (Fig. 5 (a)); the remainder of the rectangular panes have either rounded, fluid or grozed edges, most of which show pronounced concoidal fracture ripples along the chippings. The panes have been usually grozed from one side only, resulting in a slanting rim, leaving a sharp cutting edge. These grozed edges could indicate that the window-panes have been cut from larger glass sheets into the required size and shape. Both surfaces of the crown window-panes and at least one side of the rectangular fragments are smooth or glossy, while the second surface of the rectangular samples often exhibits pronounced parallel grooves (Fig. 5 (b)). It has been recently suggested that the surface structure is the most reliable indicator to distinguish between the casting and cylinder-blowing procedures. The cylinder-blown technique is thought to produce two smooth surfaces. Two distinguishable surfaces, one smooth, the other showing layered swirls, were interpreted as being the result of the viscosity of molten glass that was poured and then flattened and spread. Such swirling was observed in 80% of Late Antique window glass from Sion (Valais, Switzerland) (Kessler *et al*. 2005; Wolf *et al*. 2005).

In contrast to this interpretation, the presence of parallel grooves could also be indicative of the flattening of a round (blown) glass cylinder into a flat sheet and the concomitant accumulation of excess glass, particularly in thicker samples. Interestingly, the fragments with the most prominent grooves tend to be slightly thicker than the ones with both sides evidently smooth. The shape and arrangement of the air bubbles, as judged by microscopy, could support this hypothesis, since some of the grooved/smooth fragments have air bubbles that are distinctly

elongated (Table 1). Hence, these observations seem to be consistent with only one method of production for all the rectangular window-panes, namely the cylinder-blown technique. The fact that the crown panes were created from the same raw material by a related technique could indicate that all window types were produced in a single secondary workshop.

There does not seem to be a clear correlation between the colour and the shape and style of the window-panes (Table 1). Seventeen out of the 23 samples are of an aqua-blue colour, ranging from virtually colourless (e.g., sample 015; Fig. 5 (c)) to a light turquoise tinge (sample 018; Fig. 5 (b)); two fragments are of a light olive green (samples 003 and 023) and three of a dark, bottle green hue (samples 009, 011 and 014). Most of the windows presumably used to be translucent or nearly transparent. The overall size of the individual panes cannot be reconstructed with any certainty, but clearly exceeds 14 cm in at least one dimension in the case of the rectangular panes, and the crowns must have had diameters of 28 cm and more. Since no crown pane is preserved with its original rim, one can only speculate that their edges were folded on the basis of the rims found independently (020–023). The thickness of the samples ranges from about 1.3 to 5.9 mm with the exception of a window crown (011), with a thickness of 10.8 mm at its centre. All types of glass panes were then inserted either in a wooden window frame and held in place by lead stripes with a Z-shaped profile (Crawford 1990) or possibly directly into a plaster frame or transennae (Lamm 1928; Franz 1958; Meyer 1988). Regarding the mounting of the Petra Church windows, one example of a window edge embedded into a plaster frame has been found (O'Hea 2001). Unfortunately, this evidence is too scarce to allow any general conclusions to be drawn.

CONCLUSIONS

The window glass from the Petra Church proved to be typical soda–lime–silica glass and as a group extremely homogeneous. It thus seems reasonable to assume that all but one sample (002) derived from the same silica source. Only sample 002 diverges noticeably from the main group and appears consistent with Roman glass-making traditions, suggesting either the recycling of glass or the reuse of entire window-panes. No deliberate colouring or opacifying agents or any decolorants could be identified, either in the absorption spectra or by the ED-XRF analysis in any of the samples. Hence, iron in both oxidation states (di- and trivalent) is the only source for the various shades, ranging from colourless to yellowish-green, aqua-bluish and dark bottle green.

On the basis of principal component analyses that included various known glass groups from the Levant and Roman Italy, it was demonstrated that the glass employed for the windows in the Petra Church originated from a Levantine I source. The earliest comparable glass finds from Jalame date to the fourth century, whereas the other assemblages associated with Levantine I were from sixth- and seventh-century Dor and Apollonia. These observations bear important testimony to the trade of glass between the Levantine coast and Petra during Late Antiquity. Intriguingly, these trade networks seem to have undergone changes some time between the fourth and the seventh century. However, more comparative analytical data is required in support of this hypothesis. For the purpose of grouping and provenancing, alternative analytical methods are also needed, such as the investigation of minor and trace elements and their isotope ratios.

The chemical composition of the window glass fragments does not appear to be correlated with secondary manufacturing procedures, meaning that no unambiguous distinction between the different types of window-panes (crown glass and rectangular panes) is recognizable. The

green fragments of the assemblage, however, tend to have slightly higher silica and lower soda concentrations than the aqua-blue glass. This could be indicative of variations in the firing temperatures and/or the redox conditions in the furnace. No clear distribution of colours and/or shapes within the church building could be observed, due to the fragmentary condition of the archaeological record. Nonetheless, it has to be borne in mind that window glass needs to be considered in its architectural context, and that the ultimate purpose of windows was to provide natural illumination for an enclosed space. Windows are just as much an aesthetic and constitutive component of the architecture as the multicoloured interior decorations with which the Petra Church was richly embellished.

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