Mediterranean Archaeology and Archaeometry, Vol. 16, No 3, pp. 17-34

DOI: 10.5281/zenodo.160933

PRODUCTION TECHNOLOGY OF GLASS BRACELETS FROM THE WEST CEMETERY OF UMM EL-JIMAL IN NORTHEASTERN JORDAN

Khaled Al-Bashaireh

Department of Archaeology, Yarmouk University, Postal code 211-63, Irbid, Jordan, email: (khaledsm@email.arizona.edu)

Received: 26/03/2016
Accepted: 20/05/2016

ABSTRACT

SEM-EDX analysis is used in this study to investigate the production technology of 20 fragments of glass bracelets of uncertain date uncovered from the reused west cemetery of Umm el-Jimal in northeastern Jordan. While six bracelets are complexly decorated with multi-colored glasses, the rest are plain and mono-colored. Most of the bracelets appear macroscopically deeply colored or black. Styles and chemical analysis indicated an Islamic origin to the bracelets. Chemically, the bracelets are divided into natron, plant-ash and mixed-natron-plant-ash groups. Red, white, yellow-green decorations were produced by dispersing micron-scale copper crystals, tin oxide and lead-tin oxides in the glass melt, respectively. The results indicated recycling of older glass for the production of some bracelets and use of metal and alloy by-products as glass colorants.

KEYWORDS: Technology, Coloured Glass Bracelets, Recycling, Metal and Alloy By-Products, Umm el-Jimal, Jordan.

1. INTRODUCTION

Umm el-Jimal archaeological site is located in the governorate of Al-Mafraq, northeast Jordan (Fig. 1). From its foundation by the Nabateans during the first century AD till its abandonment at the end of the Umayyad period, the city witnessed continuous gradual developments (De Vries 1994, Al-Bashaireh 2014). The population, dimensions and structures of the city increased and it became a flourishing rural site and part of the *Limes Arabicus* defensive and trading systems (De Vries 1993,1998). The site is surrounded by cemeteries which were in continuous use from the Nabatean times during the first century AD to the Islamic periods during the seventh and eight centuries AD, and later.

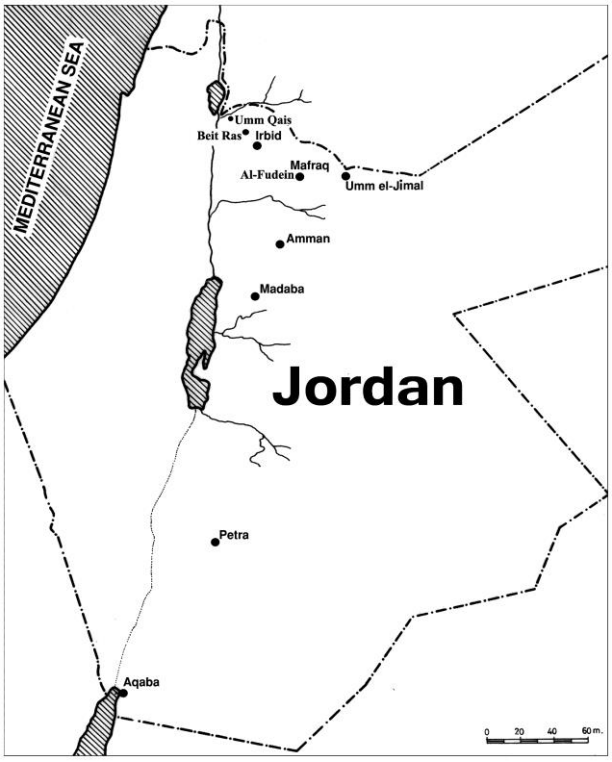


Fig. 1 Location map of Umm el-Jimal site.

2. THE ROOFED TOMB

Glass bracelets were uncovered from the western cemetery in Umm el-Jimal during a salvage excavation in 2011-2012 season. The cemetery is located in the western part of the site and bordered by modern houses from the west. It was looted extensively and most of its tombs were opened; therefore, a salvage excavation was necessary to rescue as many tombs as possible, protect the opened ones and uncover the remaining archaeological materials.

Basalt was used in building the side walls of the tombs and corbelling their roofs. The tombs lack inscriptions and are devoid of coffins, but produced fragments of ceramics, lamps, glass vessels and bracelets and bones and highly corroded coins. These artifacts indicated a continuous use of the cemetery from the first century AD till Islamic periods. One of these tombs, known as the roofed tomb produced fragments of mono and polychrome bracelets accompanied by pottery sherds, lamps and a perforated Byzantine coin which was dated to the Justinian period (AD 527-565) (Al-Housan, personal communication). Although the roofed tomb was used during the Byzantine period, no clear dates can be given to the bracelets because of its continuous use.

This study reports the results of chemical and microscopic analyses of monochrome and decorated black appearing glass bracelets discovered from the roofed tomb located at the west cemetery in Umm el-Jimal, Jordan. The study aims at the classification of the bracelets and identification of colorants, raw materials and techniques employed in their manufacture.

According to Spaer (2001), the earliest excavated glass bracelets were of small size and deep colors and well-dated to the third century AD. Afterwards, glass bracelets became widely spread in the Levant. The glasses of the third and fourth centuries were mainly plain, but few were ribbed; however, plain bracelets were produced during all periods. Bracelets with tooled or molded decorations were produced during the third century AD and became rare after the seventh century AD, twisted bracelets appeared after the fourth century AD, monochrome twisted bracelets were frequent during the Byzantine period, twisted bracelets with colored trails were common during Islamic periods, while bracelets with applied decorations are Islamic that gradually developed from simple semicircular cross sections during the early Islamic period to increasingly varied and complex decorations during the period between the thirteenth to the sixteenth centuries (Mamluk period).

In general, black appearing glass was mainly used in jewelry such as beads and bracelets and spread in the south-eastern Mediterranean region during the fourth and fifth centuries AD (Cagno et al. 2014). Usually, glass bracelets were produced by bending, twisting or non-twisting and closing a mono-color glass cane. Non twisted (seamless) bracelets were made by forcing a gather of glass melt over a cone-shaped rod and rotating so that the end product was flattened with a D-shaped cross-section. Multicolored or decorated canes were produced by adding drops, strips and patches or winding colored glass threads around a cane (Spaer 2001). Usually, decorations are the same as those of the threads of the twisted bracelets (Steiner 2008).

3. MATERIALS AND METHODS

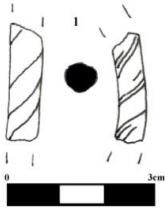
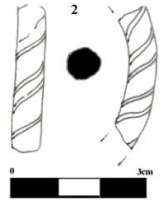
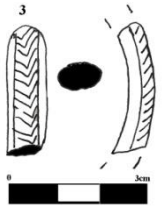
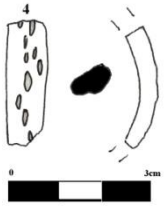
3.1. Materials

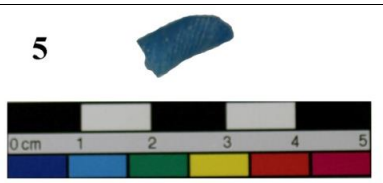
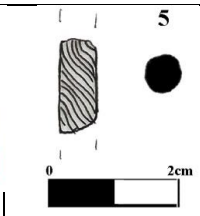
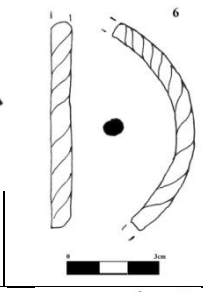
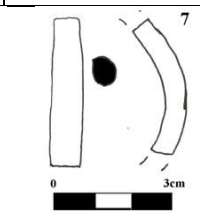
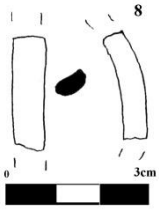
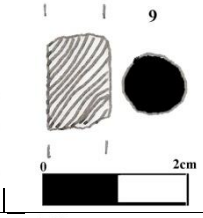
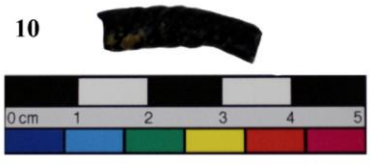
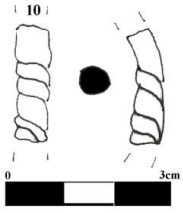
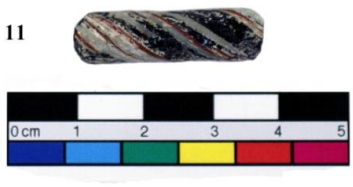
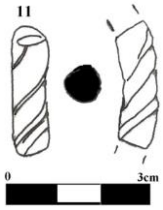
Twenty fragments of deeply colored glass bracelets were collected from the roofed tomb at the west cemetery in Umm el-Jimal archaeological site in northeastern Jordan. The glass fragments differ in color (mono-polychrome), shape (plain or twisted), diameter, and cross-sections (e.g. rounded, flattened) (Spaer 1992); for description and parallels see Table 1. Samples 1 and 11 have spirally twisted red, deeply colored yellow and gray glass threads (strips) around the bracelets cane. Twisting of samples of (1,2,6,10,11,13,18) is loose (thick), while twisting samples (5,9,12,16,17,19) is dense (fine) (see color details in Table 1).

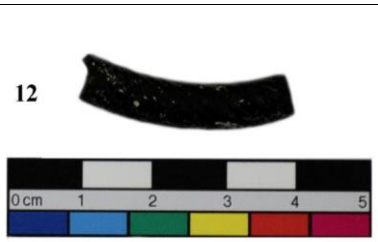
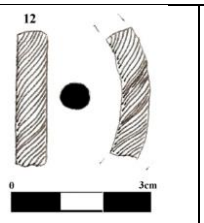
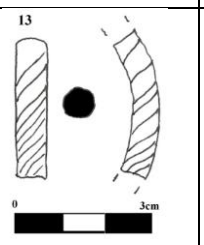
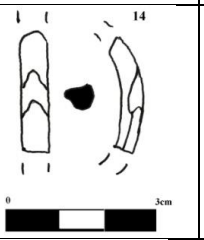
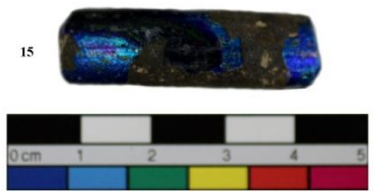
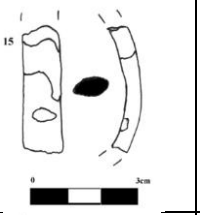
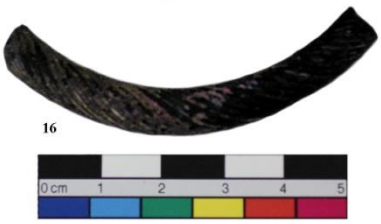
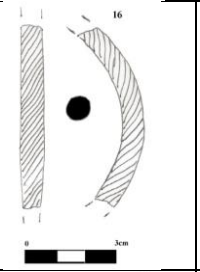
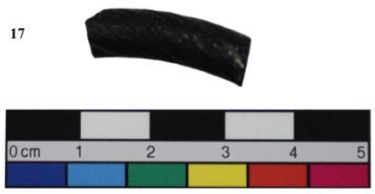
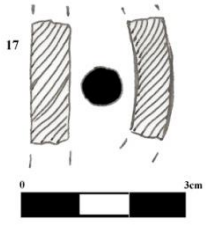
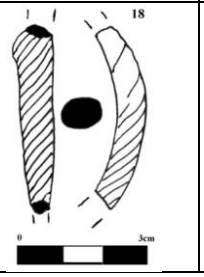
3.2. Methods

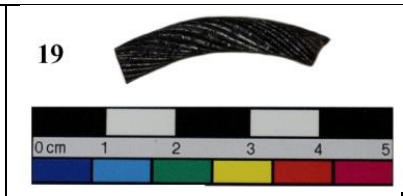
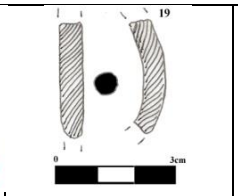
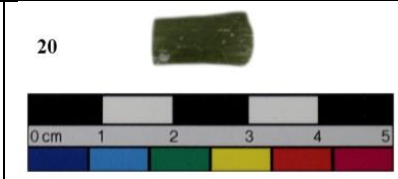
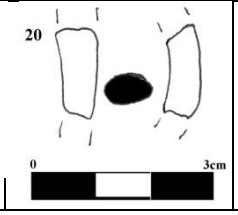
The fragments were analyzed at the Archaeological Materials Science Laboratories of the UCL Qatar. Small pieces of the samples were cut using a diamond coated thin rotating blade, embedded in cold-setting resin for 24 hours and then polished to a mirror surface using increasingly finer grades of abrasive and polishing agents, finishing with 1µm size diamond paste. The polished samples were investigated by polarized microscopy under reflected light, and then carbon coated. Their glass matrix and decorations were examined using a JEOL JSM6610LV scanning electron microscope (SEM) equipped with an Oxford Instrument XMaxN 50 energy dispersive X-ray spectrometer (EDS). Backscattered electrons were used for imaging and small-area scans and spot analyses were used to determine the major and minor oxides of the chemical composition of selected parts of the sample. The results reported in this work are representative mean values of at least five separate measurements. Measurements were ran at 20kV, working distance 10mm, process time 5, livetime 60 sec. The energy of the beam was calibrated regularly by analyzing a cobalt standard and adjusting the spot size to achieve a deadtime of c. 40%. Analyses were done using the Aztec software and oxides are evaluated stoichiometrically.

Table 1. Description, photos, drawing and parallels of the samples (Drawings by Mahmoud Omari).

Description	Photos	Drawings	Parallels
S.1 Spirally twisted, circular section, deep brown-purple core, with added asymmetrically fused trails.			Boulogne and Henderson (2009): Page 61, fig. 1:239 (Mamluk–Ottoman). Steiner 2008: Page 3, fig. 2:b and d, (Mamluk). Spaer (1992): page 50, fig.6. (Most Islamic periods). Saper (2001): Page 368, plate 35: 468 (L. Ottoman – 19th C. AD). Meyer (1992): plate 20: 562-565, (L. Ayyubid-Mamluk, 14thC AD).
S.2 Spirally twisted, circular section, with light and deep colored greenish blue hues.			Spaer (2001): page 368: plate 35, N.467 (Early Islamic-8th C.).
S.3 Semicircular section, with front applied colored decorations of blue and white concentric V shapes, deep brown-purple core.			Boulogne and Hardy-Guilbert (2010): page 137, fig. 3h and page 138 fig. 5e (sixteenth–seventeenth centuries). Meyer (1992): plate 20: 579. (Islamic; L. Ayyubid-Mamluk, ~14thC AD).
S.4 Semicircular section, with colored decorations of crumbs (specks) or prunts, deep brown-purple core.			Walker et al. (2007): Page 461, fig. 34: R31 (Mamluk). Spaer (2001): pages 202 and 368: plate 35: 469 (Pre Ottoman –Islamic period). Spaer (1992): page 51, fig. 8 and fig. 24: 5, (Early Islamic, Pre-Ottoman). Boulogne (2008): page 150, plate 2, group 1:G, (Mamluk).

S.5 Spirally finely twisted, circular section, monochrome, aqua monochrome, without further decoration.			Steiner (2008): Page 3, fig. 2:c (Mamluk). Spaer (2001): page 201: 462-464, and page 368: plate 35:462-464, (4thC and later). Boulogne and Henderson (2009): fig.1: 377 (Mamluk-Ottoman).
S.6 Spirally finely twisted, circular section, deep brown-purple core, monochrome, without further decoration.			Walker et al. (2007): Page 462: R27 (Mamluk-Ottoman). Spaer (2001): page 201: 462-464, and page 368: plate 35: 4th c. AD–and later).
S.7 Semicircular section, plain, deep brown-purple core.			Boulogne and Henderson (2009): Page 63, fig. 3:314 (Mamluk-Ottoman). Boulogne and Henderson (2009): table 1: page 55. Steiner (2008): page 3, fig. 2:a (Mamluk). Meyer (1992): plate 20: 556-558 (L. Ayyubid-Mamluk, 14thC AD). Spaer (2001): page 366, plate 33: 438-439, (L. Roman-Byzantine, or later).
S.8 Semicircular-circular section, plain, deep colored green core.			Spaer (2001): page 366, plate 33: 437-9, (L. Roman-Byzantine, or later). Boulogne and Henderson (2009): page 63, fig. 3:314 (Mamluk-Ottoman). Meyer (1992): plate 20: 556-558 (L. Ayyubid-Mamluk, 14thC AD). Steiner (2008): page 3, fig. 2:a (Mamluk). Boulogne and Henderson (2009): table 1: page 55 (Mamluk–Ottoman periods, Pre-Islamic-Islamic).
S.9 Spirally finely twisted, deep colored blue core, monochrome without further decoration.			Walker et al. (2007): page 462:R27 (Mamluk-Ottoman). Spaer (2001): page 201: 462-464, (4thC AD and later).
S.10 Spirally twisted, semicircular section, deep colored blue core, monochrome without further decoration.			Walker et al. (2007): page 462: R29 (Mamluk-Ottoman). Spaer (2001): page 201: 462-465 (4thC AD and later).
S.11 Spirally twisted, circular section, deep brown-purple core, with asymmetrically fused trails.			Boulogne and Hardy-Guilbert (2010): page 137, fig. 3p,q and page 138 fig. 5j (sixteenth–seventeenth centuries). Steiner (2008): page 3, fig. 2:b,d (Mamluk). Boulogne and Henderson (2009): page 61, fig. 1:239 (Mamluk-Ottoman). Spaer (1992): page 50, fig. 6 (Pre-Ottoman). Saper (2001): page 368, plate 35: 468 (L. Ottoman–19thC AD).

S.12 Spirally finely twisted, circular section, deep colored blue core, monochrome without further decoration			Walker et al. (2007): page 462: R29 (Mamluk-Ottoman). Spaer (2001): page 201:462-465 (4thC and later).
S.13 Spirally finely twisted, circular section, deep brown-purple core, monochrome without further decoration			Walker et al. (2007): page 462: R27 (Mamluk-Ottoman). Spaer (2001): page 201:462-465 (4thC and later).
S.14 Semicircular section, deep colored blue core, with added colored patches.			Spaer (1992): page 52, fig. 14 (Maluk-Ottoman). Spaer (2001): page 203: 474, (L. ottoman).
S.15 Semicircular section, plain, deep colored green core.			Boulogne and Henderson (2009): page 63, fig. 3:314 (Mamluk–Ottoman). Meyer (1992): plate 20: 556-558 (L. Ayyubid-Mamluk, 14thC AD). Spaer (2001): pages 199 and page 366, plate 33:438-439 (L. Roman - Byzantine or later).
S.16 Spirally finely twisted, circular section, deep brown-purple core, monochrome without further decoration.			Walker et al. (2007): page 462:R27 (Mamluk-Ottoman). Spaer (2001): page 201: 462-46 (4thC AD and later).
S.17 Spirally finely twisted, circular section, deep brown-purple core, monochrome without further decoration.			Walker et al. (2007): page 462:R29 (Mamluk-Ottoman). Spaer (2001): page 201: 462-46 (4thC AD and later).
S.18 finely twisted, semicircular section, deep brown-purple core, deteriorated.			Walker et al. (2007): page 462:R29 (Mamluk-Ottoman). Spaer (2001): page 201:462-46 (4thC AD and later).

S.19 Spirally finely twisted, circular section, deep brown-purple core, without further decorations	 	Walker et al. (2007): page 462:R27 (Mamluk-Ottoman). Spaer (2001): page 201: 462-46 (4thC and later).
S.20 yellowish green, semicircular section	 	Spaer (2001): page 193 and page 366: plate 33: 439, and also 437-442 (L. Roman-Byzantine or later). Spaer (1988): page 54, fig.1 (3rdC AD onwards but not before the Byzantine period).

The instrument performance was tested against the recommended values for the Corning Museum ancient glass standards A, B, C and D (Brill 1999) analyzed under the same conditions as the glass samples (Table 2). They showed a very good agreement including low concentrations below 0.5wt% (for more details see Rehren and Nixon 2014). The precisions of the analyses are given as relative standard deviations (RSD), while the accuracies are given as percent relative errors (PE), (Table 2); for more details see Kuisma-Kursula (2000:113).

Table 2. Comparison of measured values (M.V.) from SEM-EDX and given (known) values (G.V.) for corning standards A,B,C,D. Accuracies (percent error (PE)) and precisions (relative standard deviation (RSD)) are also presented. Accuracy levels of the measured standards are close; however, accuracy levels of Na_2O and SiO_2 were improved when corning D and B were considered, respectively.

Corning standards analyses																		
	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO_2	Fe_2O_3	CoO	CuO	ZnO	Sb_2O_5	BaO	PbO
Corning standard A																		
M. V.	14.23	2.58	0.88	67.32	-	0.18	0.10	2.95	5.27	0.82	1.07	1.10	0.17	1.20	-	1.99	0.56	-
G. V.	14.30	2.66	1.00	66.56	0.13	0.16	0.10	2.87	5.03	0.79	1.00	1.09	0.17	1.17	0.04	1.75	0.56	0.12
PE	0.47	2.94	12.50	1.15	-	11.46	1.67	2.61	4.67	3.80	7.17	0.61	0.00	2.71	-	13.71	0.89	-
RSD	0.17	0.02	0.02	0.30	-	0.02	0.00	0.04	0.04	0.04	0.03	0.05	0.01	0.03	-	0.11	0.04	-
Corning standard B																		
M. V.	16.85	1.03	4.12	62.28	0.86	0.64	0.18	1.08	8.98	0.13	0.26	0.38	-	2.85	0.21	0.73	-	0.58
G. V.	17.00	1.03	4.36	61.55	0.82	0.54	-	1.00	8.56	0.09	0.25	0.34	0.05	2.66	0.19	0.46	0.12	0.61
PE	0.88	0.49	5.58	1.18	5.28	19.14	10.00	7.83	4.89	47.94	2.00	10.78	-	7.14	11.40	58.70	-	5.19
RSD	0.23	0.02	0.05	0.09	0.04	0.04	0.01	0.02	0.03	0.03	0.02	0.03	-	0.05	0.09	0.09	-	0.05
Corning standard C																		
M. V.	1.03	2.62	0.78	33.43	-	-	-	2.86	5.09	0.81	-	0.36	0.18	1.19	-	-	12.34	39.25
G. V.	1.07	2.76	0.87	34.87	0.14	0.16	0.20	2.84	5.07	0.79	-	0.34	0.18	1.13	0.05	0.03	11.40	36.70
PE	4.21	5.13	10.15	4.12	-	-	-	0.76	0.39	1.90	-	6.86	2.78	5.31	-	-	8.22	6.96
RSD	0.04	0.03	0.03	0.14	-	-	0.03	0.05	0.06	0.04	0.03	0.07	-	-	-	-	0.11	0.16
Corning standard D																		
M. V.	1.33	3.97	5.13	55.70	4.17	0.24	0.17	11.71	15.30	0.43	0.57	0.52	-	0.39	-	1.41	0.38	0.30
G. V.	1.20	3.94	5.30	55.24	3.93	0.30	-	11.30	14.80	0.38	0.55	0.52	0.02	0.38	0.10	0.97	0.51	0.48
PE	10.69	0.68	3.24	0.84	6.11	19.44	43.33	3.58	3.40	11.84	3.64	0.00	-	2.63	-	45.53	25.16	38.54
RSD	0.03	0.05	0.05	0.16	0.05	0.03	0.01	0.06	0.09	0.06	0.04	0.03	-	0.05	-	0.14	0.06	0.05

4. RESULTS AND DISCUSSION:

4.1. Shaping methods

Because the bracelets under investigation are fragments, it is difficult to tell which of the two techniques explained above was used to shape each of them. However, it is very likely that the bracelets of circular cross-section and twisted (1,2,5,6,9,10,11,12,13,16,17,18,19) (Table 1) were shaped by the cane-joining technique, while the bracelets (3,4,7,8,14,15,20) with flat (or semicircular) cross-section were shaped by the second one. In general, mono-colored bracelets of flat cross-section (such as 7,8,15,20) are older in age than those of circular cross-section and multi-colored ones (Spaer 2001; Steiner 2008).

4.2. Composition and style

Table 3 and oxide bi-plots of Fig. 2 report the chemical composition of the canes and colored deco-

rations. The samples can be defined as silica-soda-lime-glass. Minimum and maximum ranges of these three components are 60.90-73.72%, 9.43-19.75% and 3.92-10.84%, respectively. MgO and K_2O values of the canes and their distribution in MgO-K_2O bi-plot of Fig. 2 can be used to classify Umm el-Jimal glass bracelets into three groups; natron-glass (less than 1.5%), plant-ash glass (more than 2.25%) and mixed natron-plant ash glass (between 1.5 and 2.25%) (Henderson 1985, 1991; Arletti et al. 2010; Bugoi et al. 2013).

Accordingly, samples 5,7,8,15 and 20 are natron-glasses, samples 2,6,10,11,12,13,14,17, 18,19 are plant-ash glasses, while samples 1,4 and 16 are mixed natron-plant ash glasses. Sample 3 is characterized by elevated potassium and low concentrations of magnesium oxide (< 0.6%), aluminum oxide (0.82%), calcium oxide (< 4%), while its total alkali contents is 19.2% (Henderson 2006), so it represents a different type of glass called a mineral glass produced using an alkali-rich mineral other than natron, for more details on the interpretation of this kind of glass see Boulogne and Henderson (2009:73).

It is worth mentioning that for each of the decorated samples (1,2,3,4,11 and 14) the canes and colored decorations (threads, strips, prunts, patches) have similar MgO and K_2O values (Fig. 2). Colored glasses and the cane of sample 1 have a mixed natron-plant ash composition, while those of samples 2,4,11 and 14 have plant ash compositions. It is likely that colorants used to produce the decorations were added to the same glass melt used in the production of the canes (except the white color of sample 11).

Natron-glass with low potash and magnesia dominated the Mediterranean and Europe from the Roman through to the early Islamic periods (Freestone et al. 2002a,b). However, glass production changed during the second half of the fourth century to the production of HIMT glass (Aerts et al. 2000; Foster and Jackson 2009). Stylistic changes included the use of tableware forms and deeply colored green and brown, while the chemical composition showed higher concentrations of iron, manganese, titanium and some trace elements like copper.

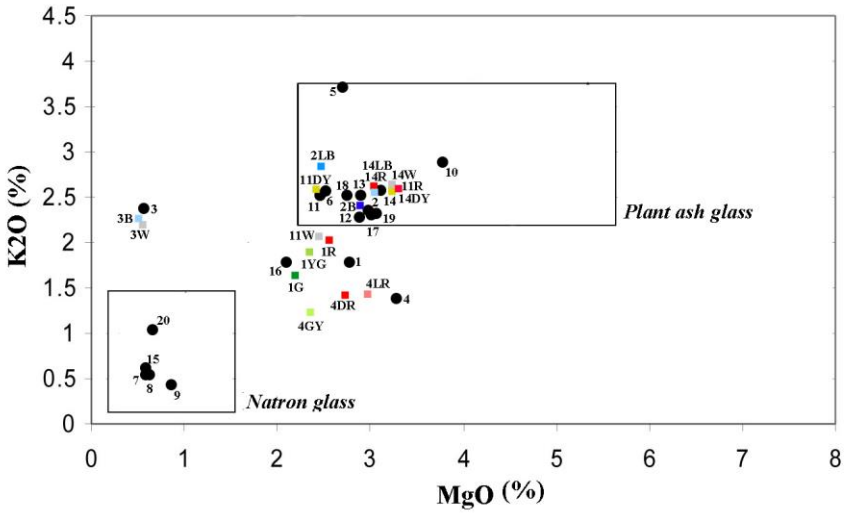


Fig. 2 Plot of the MgO versus the K_2O concentration in the analysed glass bracelets

Aerts et al. (2000) explained this change in glass composition to the introduction of impurities by recycling older glass or use of new impure raw materials. After the fourth century, glass compositional changes indicate that further changes in sand composition occurred, suggesting changes in the location of the primary production of natron glass in Egypt and on the Levantine coast (Freestone et al. 2000). In the Levantine region, Byzantine glasses became higher in CaO and Al_2O_3 and lower in Na_2O than in the 1-4th centuries (Tal et al. 2008; Rehren et al. 2010) and it appears that Apollonia-Arsuf was a major production center for this type of glass (Tal et al. 2004; Freestone et al. 2008). By the Umayyad period, production had shifted to Bet Eli'ezer, producing a glass with particularly low soda and high alumina, reflecting a shortage of natron flux (Shortland et al. 2006; Freestone et al. 2015); however, one should keep in mind that it is likely to have been other primary glass production centres that have not yet been discovered and others that have been destroyed. By the mid-ninth century there was a major compositional change when natron was replaced by soda-rich plant ash and the glasses have higher K_2O, MgO and P_2O_5 (Henderson et al. 2004).

The general trend of these changes in glass composition is obvious between the three groups of Umm el-Jimal bracelets. The averages show an increase in magnesia, potash and phosphorus and a decrease in soda and alumina. The difference in alumina and potash values indicates the use of different sand sources; see Table 3, (Ganio et al. 2012). The low values of alumina and lime in some samples suggest the use of sand or ash poor in carbonates and feldspar. Increased concentrations of potash compared to magnesia in samples 3 and 20 might be explained by prolonged glass working and/or ash and vapor from the fuel (Paynter 2008; Tal et al. 2008; Rehren et al. 2010).

Based on the styles of the bracelets under investigation discussed above, the samples are probably Islamic from Mamluk-Ottoman periods, (Table 1). On the contrary, the chemical analyses suggest a different chronological sequence to the three groups mentioned above. The first group could be dated to the Roman period, the third group to Islamic periods after the Umayyad period, while the second group to the transition period including the late Byzantine and Umayyad periods (Dussart et al. 2004).

It is worth noting the contradiction between stylistic and chemical dates of samples 1 and 4. These samples have complex decorations; therefore, it is unlikely to be pre-Islamic (Spaer 2001). It is not easy to decide whether the bracelets were produced from raw materials or recycled glass or a combination of both. However, because of the scarcity of natron supplies during and after the transition period, it is likely that mineral alkali or mixed natron-plant ash compositions were produced by mixing plant ash and natron glasses or plant ash fluxes with remaining natron glass cullets as proposed by Henderson (2002), Uboldi and Verita (2003); Dussart et al. (2004); Lauwers et al. (2010); Silvestri and Marcante (2011) and Bugoi et al. (2013). The presence of considerable percentages of titanium, manganese and iron in Umm el-Jimal bracelets' canes and the positive correlation among K_2O and MgO (R^2=0.49) support this hypothesis.

The amounts of lime and alumina present in the bracelets reflect the amounts of shells, limestone and feldspar in the sand and lime in the ash (Freestone et al. 2000). Based on the diagrams of Silvestri and Marcante (2011: Fig. 4: page 2517), samples 7,8,9,15 and sample 20 are located in the compositional areas of Levantine I and Levantine II, respectively. Because samples 7,8,9,15 are Mamluk in age but reflect Levantine I glass, it can be concluded that Levantine I glass was recycled to produce them. On the contrary, sample 20 has the Levantine II glass composition and dated differently to the late Roman – Byzantine period or after the Byzantine period (Table 1). The chemical composition might suggest an original Levatine II glass to this sample for the first date or recycling Levantine II glass for the second date. Most of the studied samples of the tomb are Islamic, so it is likely that this sample is similar in age and belongs to one of the Islamic periods.

4.3. Bracelets colorants

Glass color and opacity depend on different factors mainly the quantity and ionic form of minor metal oxides present in the glass and the kiln's firing (redox) conditions. For example, Fe(II) ions give green or blue colors, while Fe(III) ions give brown-yellow colors depending on the kiln's environment. The opacity and black appearance of a colored glass bracelet occur due to its high content of certain metal particles dispersed in the matrix and/or the bracelet thickness (Cagno et al. 2013, 2014).

4.3.1. Monocolored bracelets

Fourteen bracelets have different monocolors (Table 1). Deeply violet/brown color of the canes of the decorated sample 1 and samples 6,11,13,16,17, and 19 owe their color to elevated values of manganese oxide ranging from 2.14 to 5.27% and moderate iron values ranging between 0.61 and 0.97% except sample 16 with a value of 2.34% (Table 3). Normal manganese oxide content in glass is about 200 ppm which is derived from siliceous sand impurities (Freestone et al. 2015). The high MnO values indicate their intentional addition to the glass batch.

The blue color of sample 9 is likely produced by its cobalt content (0.22%) seen in most ancient blue soda-lime-silica glass (Schibille and Freestone 2013). Sample 5 is aqua colored and samples 10,12,14 are deeply colored blue. It is possible that undetected cobalt (detection limit is 0.1%) colored these samples blue or/and copper in samples 5 (0.65%) and 12 (3.15%) are their blue color agents. The presence of both copper and tin in sample 5 might indicate their addition as "bronze scale" (Goffer 2007:157) in the form of powders or small particles. The blue color of sample 10 is likely results from the kiln's reducing atmosphere produced Fe(II) ions.

Table 3. Chemical analyses of the Umm el-Jimal monocoloured bracelets and decorated bracelets.

S	Color	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO2	Fe_2O_3	CoO	CuO	As_2O_3	Ag_2O	$Sn0_2$	Sb_20_5	NiO	PbO	Bi_2O_3	ZnO	Total	
Monocolored samples																									
5	Blue/Aqua	13.56	2.79	0.44	69.67	0.38	0.25	0.87	3.73	7.32	-	-	0.25	-	0.69	-	-	0.25	-	-	-	-	-	100.21	
6	Brown/purple	11.25	2.47	1.16	67.83	0.41	0.24	0.96	2.56	8.94	0.21	3.39	0.64	-	-	-	-	-	-	-	-	-	-	100.07	
7	Black	14.17	0.61	2.14	60.90	-	0.22	0.86	0.64	7.34	0.14	0.87	12.42	-	-	-	-	-	-	-	-	-	-	100.31	
8	Dark Green	15.57	0.65	2.46	63.40	-	0.24	0.99	0.52	8.70	0.16	0.95	6.51	-	-	-	-	-	-	-	-	-	-	100.14	
9	Dark Blue	19.75	0.80	2.34	65.40	-	0.45	1.13	0.47	6.51	0.29	0.24	2.03	0.22	0.24	-	-	-	-	-	0.43	-	-	100.31	
10	Dark Blue	11.33	3.77	1.06	66.94	0.33	0.24	0.76	2.83	9.61	0.17	1.33	1.09	-	-	-	-	-	-	-	-	-	-	99.46	
12	Dark Blue	12.18	2.93	0.55	67.77	0.21	0.24	0.84	2.33	8.33	0.16	1.16	0.38	-	3.15	-	-	-	-	-	-	-	-	100.23	
13	Brownish purple	9.43	2.93	1.81	66.54	0.37	0.29	0.80	2.53	9.00	0.21	5.27	0.94	-	-	-	-	-	-	-	-	-	-	100.11	
15	Dark Green	16.69	0.64	2.38	61.75	0.11	0.29	1.04	0.58	8.31	0.10	1.05	7.13	-	-	-	-	-	-	-	-	-	-	100.05	
16	Brownish purple	9.52	3.43	1.15	68.87	0.29	0.33	0.71	2.49	8.88	0.14	3.56	0.63	-	-	-	-	-	-	-	-	-	-	100.00	
17	Brownish purple	11.87	3.02	1.47	67.47	0.36	0.33	0.77	2.35	8.77	0.20	2.82	0.62	-	-	-	-	-	-	-	-	-	-	100.04	
18	Black	19.09	2.73	1.67	64.31	0.40	0.75	1.53	2.51	6.35	0.15	-	0.62	-	-	-	-	-	-	-	-	-	-	100.11	
19	Brownish purple	9.43	3.09	1.29	70.09	0.30	0.31	0.73	2.41	8.56	0.18	3.01	0.61	-	-	-	-	0.88	-	-	-	-	-	100.89	
20	Green/Yellowish	14.76	0.67	2.88	68.74	0.10	-	0.69	1.17	10.33	-	0.18	0.57	-	-	-	-	-	-	-	-	-	-	100.09	
Decorated Samples																									
1	Red	9.48	2.60	1.11	57.42	-	-	0.77	2.05	7.39	0.12	0.82	5.33	-	1.09	-	-	3.38	-	-	8.45	-	-	100.01	
	Green	7.99	2.21	0.85	50.38	0.24	-	0.72	1.65	6.24	-	0.73	0.53	-	1.73	-	-	4.09	-	-	22.61	-	-	99.96	
	Yellowish green	9.13	2.42	0.88	55.66	0.22	-	0.74	1.88	6.88	-	0.83	0.47	-	-	-	-	3.24	-	-	17.59	-	-	99.96	
	Matrix Brownish violet/	10.96	2.82	1.26	68.48	0.32	-	1.02	1.71	8.54	0.18	3.93	0.79	-	-	-	-		-	-		-	-	100.00	
2	Dark blue	11.73	2.95	1.04	66.22	0.13	-	0.77	2.37	9.04	0.07		0.55	-	-	-	-	1.04	0.07	-	3.38	-	-	99.35	
	Light blue	12.60	2.54	1.17	67.31	0.21	0.29	0.81	2.79	9.72	-	0.41	0.52	-	2.70	-	-			-		-	-	101.06	
	Light yellow Matrix	11.62	2.84	1.21	64.54	0.13	0.30	0.81	2.59	10.84	0.06	0.36	0.53	-	-	-	-	-	-	-	-	-	-	95.81	
3	White	15.81	0.50	0.78	69.82	-	-	1.20	2.25	3.58	0.15	-	0.29	-	-	-	-	1.28	-	-	4.36	-	-	100.00	
	Blue	15.66	0.49	0.80	73.56	-	-	1.26	2.31	3.84	0.17	-	0.59	0.36	-	0.59	-	-	-	-	-	-	-	99.64	
	Matrix Yellow	16.79	0.58	0.82	73.72	-	-	1.28	2.41	3.92	0.17	-	0.28	-	-	-	-	-	-	-	-	-	-	99.97	

4	Dark red	16.11	2.81	0.97	58.76	0.07	-	1.07	1.43	7.56	-	-	3.37	-	2.38	-	-	0.95	-	-	4.54	-	-	100.00	
	Light red	17.07	2.95	0.96	61.32	-	0.27	1.11	1.45	7.65	-	-	4.49	-	2.75	-	-		-	-	-	-	-	100.00	
	Greenish yellow	13.75	2.39	0.80	52.64	-	-	0.95	1.26	6.09	-	-	0.30	-		-	-	2.27	-	-	19.47	-	-	99.91	
11	Red	9.63	3.26	1.41	59.38	0.27	-	0.76	2.64	9.70	-	1.13	2.96	-	2.64	-	-	-	-	-	-	-	-		
	White	7.82	2.55	1.11	53.76	-	-	0.65	2.12	7.15	0.06	0.82	0.66	-	-	-	-	-	-	-	6.23	-	-	100.01	
	Yellow middle sample	11.29	2.49	1.14	67.83	0.34	0.09	0.97	2.56	9.00	0.15	3.50	0.65	-	-	-	-	7.22	-	-	16.09	-	-	100.00	
	with white lines Yellow	11.04	2.55	1.17	67.19	0.21	-	0.89	2.46	9.09	0.13	3.29	0.82	-	0.16	-	-	-	-	-	-	-	-	99.98	
	purple matrix Brownish	11.27	2.52	1.17	67.80	0.37	0.12	0.94	2.52	8.93	0.20	3.57	0.63	-		-	-	-	-	-	1.00	-	-	100.01	
14	Red	11.07	3.10	1.59	63.40	0.25	-	0.63	2.60	8.53	0.21	0.94	3.73	-	1.47	-	-	-	-	-	-	-	-	100.03	
	Yellow	11.57	3.19	1.20	64.69	-	-	0.73	2.53	8.32	0.19	0.90	0.56	-	0.29	-	-	-	-	-	2.61	-	-	100.13	
	White	12.08	3.24	1.21	66.48	-	-	0.76	2.57	8.54	0.07	0.89	0.57	-		-	-	-	-	-	6.11	-	-	100.27	
	Matrix blue	12.10	3.14	1.59	68.54	-	-	0.78	2.55	8.93	0.19	1.09	0.92	-	-	-	-	0.88	-	-	2.79	-	-	100.04	
Single spectrum																									
S	Spectrum Label	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO2	Fe_2O_3	CoO	CuO	As_2O_3	Ag_2O	$Sn0_2$	Sb_20_5	NiO	PbO	Bi_2O_3	ZnO	Total	Pigment
1	Spectrum 636	-	-	-	-	-	-	-	-	-	-	-	0.21		82.89	2.2	0.47	2.27	3.69	-	8.26	-	-	99.99	In red
2	Spectrum 264	0.38	-	-	1.98	-	-	-	-	-	-	-	-	-	-	-	-	97.64	-	-		-	-	100	In dark blue
3	Spectrum 312	9.84	0.23	0.41	26.98	-	-	0.37	0.62	1.64	-	-	0.56	-	-		-	36.49	-	-	21.89	-	0.96	99.99	In white
3	Spectrum 319	15.74	0.48	0.80	71.23	-	-	1.22	2.37	3.59	0.16	-	1.08	0.83	-	0.90	-	-	-	0.29	-	1.30	-	99.99	In blue
3	Spectrum 320	15.41	0.49	0.81	72.13	-	-	1.21	2.35	3.60	0.19	-	0.89	0.67	-	0.90	-	-	-	0.13	-	1.22	-	100	In blue
3	Spectrum 321	13.81	0.51	0.77	72.54	-	-	1.27	2.39	3.75	0.20	-	0.90	0.74	-	0.70	-	-	-	0.27	-	2.15	-	100	In blue
3	Spectrum 323	14.89	0.48	0.80	71.29	-	-	1.21	2.41	3.72	0.15	-	1.32	1.16	-	0.93	-	-	-	0.32	-	1.33	-	100.01	In blue
3	Spectrum 324	4.79	-	-	9.41	-	-	0.11	0.22	0.43	-	-	0.69	13.13	-		-	-	-	71.22	-	-	-	100	In blue
3	Spectrum 325	16.27	0.51	0.84	72.76	-	-	1.23	2.34	3.76	0.15	-	0.67	0.45	-	0.47	-	-	-		-	0.58	-	100.03	In blue
3	Spectrum 326	16.41	0.50	0.84	73.09	-	-	1.23	2.38	3.80	0.14	-	0.49	0.39	-	0.31	-	-	-	0.17	-	0.24	-	99.99	In blue
3	Spectrum 327	16.66	0.52	0.79	73.12	-	-	1.25	2.34	3.72	0.10	-	0.50	0.33	-	0.27	-	-	-	-	-	0.38	-	99.98	In blue
3	Spectrum 328	16.61	0.54	0.81	73.43	-	-	1.21	2.35	3.76	0.17	-	0.59	0.32	-	0.20	-	-	-	-	-	-	-	99.99	In blue
3	Spectrum 329	16.64	0.52	0.84	73.40	-	-	1.23	2.38	3.84	0.16	-	0.49	0.30	-	0.21	-	-	-	-	-	-	-	100.01	In blue
3	Spectrum 330	16.49	0.51	0.81	72.98	-	-	1.24	2.36	3.78	0.12	-	0.56	0.40	-	0.30	-	-	-	-	-	0.45	-	100	In blue
3	Spectrum 399	-	-	-	0.71	-	-	-	-	-	-	-	-	-	0.38	-	-	98.91	-	-	-	-	-	100	In white

4	Spectrum 413	-	-	-	-	-	-	-	-	0.11	-		0.55	-	99.34	-	-	-	-	-	-	-	-	100	In red
7	Spectrum 8	-	-	0.32	0.65	-	-	-	-	-	0.11	0.29	98.63	-	-	-	-	-	-	-	-	-	-	100	In black
14	Spectrum 495	0.26	-	-	6.04	-	-	-	-	-	-	-	0.24	-	-	-	-	26.53	-	-	66.92	-	-	99.99	In yellow
14	Spectrum 496	1.17	-	-	8.75	-	-	-	-	0.74	-	-	0.30	-	-	-	-	25.28	-	-	63.76	-	-	100	In yellow
14	Spectrum 497	0.87	0.21	-	7.36	-	-	-	-	-	-	-	0.26	-	-	-	-	27.23	-	-	64.07	-	-	100	In yellow
14	Spectrum 498	0.64	-	-	6.52	-	-	-	-	-	-	-	0.17	-	-	-	-	30.11	-	-	62.56	-	-	100	In yellow
14	Spectrum 499	0.38	-	0.2	6.33	-	-	-	-	-	-	-	0.27	-	-	-	-	28.89	-	-	63.94	-	-	100.01	In yellow

Deeply green color and black appearance of bracelets 8 and 15 are most likely a result of their high values of iron oxide (6.5% and 7.1%, respectively) which are intentionally added to the glass. Sample 7 represents a special case, it has the common silica-soda-lime composition fluxed with natron, both K_2O and MgO values are lower than 0.65%. This sample was colored black by deliberate addition of a high percentage of iron oxide reaching a value of 12.4% (Table 3). SEM analyses showed small particles of pure iron oxide (98.6%) dispersed in the glass in different shapes; elongated, flat, rounded, semi-rectangular (Fig. 3). Back-scattered electron analyses revealed that the glass is inhomogeneous and poorly mixed where some areas have high concentrations of iron oxide and iron particles nearly dissolved in the glass melt. It is likely these particles were deliberately added during the bracelets shaping at a secondary workshop as flakes of hammer scale that resemble a waste material of iron smithing that comprises about 95-99% magnetite and wüstite (Young 2011). This result is supported by the finding of Rehren et al. (2012) and Cholakova and Rehren (2014) who showed the first direct evidence of using residual iron oxide particles in the production of Roman black glass instead of natural magnetite rich sands or iron ores suggested by Van der Linden et al. (2009).

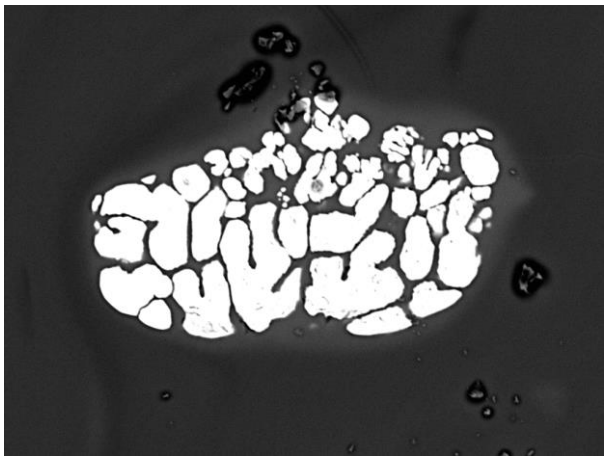


Fig. 3 A backscatter electron image of an iron oxide particle of the bracelet of black sample 7 from Umm el-Jimal suggesting the addition of hammer scale iron flakes (spectrum 8).

It is worth mentioning that not all the samples have enough Fe-content to give rise to deeply color the samples (Table 1), so it is assumed that the thickness and shape of the bracelets play a major role in the perception of color.

In contrast, the yellowish green sample 20 has low iron content (0.57%); however, the occasional presence of manganese (0.18%) in proper control of the furnace atmosphere might caused this color by oxidizing Fe(II) to Fe(III) (Mirti et al. 2001). Samples 4 and 18 are deeply colored and look black, but very small thin pieces of these samples appeared yellow when examined under a stereomicroscope. The yellow color was probably produced under fairly strong reducing firing environments for iron and sulphate ions, for more details see Van der Linden et al. (2009).

4.3.2. Decorated bracelets

The red decorations of bracelets 1, 4, 11 and 14 were most likely produced by a deliberate addition of elevated amounts of copper (1.09-2.64%), iron (2.96-5.33%) and lead (2.61-8.45%) compared to their canes' composition (Fig. 4). Glassmakers produced opaque red glass by disseminating micron-sized crystals of metallic copper in the glass matrix (Fig. 5, Fiori 2015). The reduction environment of the kiln enhanced by intentional addition of high levels of iron oxide to the batch caused the reduction and then precipitation of copper from the melt in the form of tiny metallic copper particles, which impart the red color and opacity to the glass (Ahmed and Ashour 1981; Brill and Cahill 1988; Freestone et al. 2003). Based on Freestone (1987), the red colorations under investigation can be classified as low-lead and low-copper red glass (less than 12% of lead oxide PbO and 5% of copper oxide Cu_2O). The function of lead in the low-lead and low-copper opaque red glass is to form a large number of copper particles in the glass melt despite their size and improve the opacity and intensity of the color (Freestone 1987; Barber et al. 2009). Higher values of lead oxide dissolve more copper into the glass and form brighter (sealing-wax) red color compared to the samples with lower value (Freestone 1987). Furthermore, high amounts of lead make the glass less susceptible to devitrification (Brill and Cahill 1988).

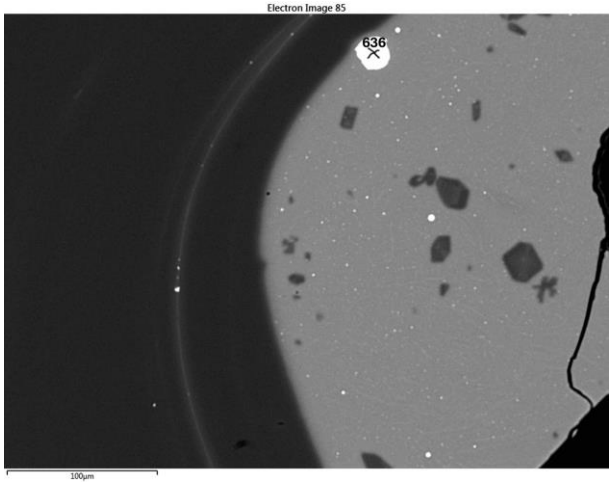


Fig. 4 A backscatter electron image of red color decoration of sample 1 from Umm el-Jimal showing elevated amounts of copper, iron and lead compared to the canes' composition (spectrum 636).

It is likely that the presence of tin oxide in the red decorations of samples 1 (3.38%) and 4 (0.95%) promotes the precipitation of copper particles. Ram et al. (1970) found that Sn^{++} retards the reduction of Cu^{+} to Cu^{o} in the glass melt which remains suitable for the production of red colour for a considerable period. The presence of tin oxide might indicate the recycling of pewter (Pb-Sn alloy) and bronze (Cu-Sn alloy), while high values of iron oxide might indicate the use iron scraps (Peake and Freestone 2012).

The blue decoration of bracelet 3 contains cobalt oxide associated with arsenic (0.59%), magnesium (0.49%), Nickel (0.41%) and aluminum (0.80%), high potassium (2.31%) and lacks lead, manganese, sulfur and copper. This might indicate the use of Erythrite (cobalt bloom), $Co_3(AsO_4).8H_2O$, characterized by cobalt and arsenic, which is a secondary hydrated cobalt arsenate mineral from cobalt deposits such as cobaltite (Henderson 2006).

Fig. 5 A backscatter electron image of red color decoration of sample 4 from Umm el-Jimal showing copper particles disseminated in red glass (spectrum 413).

The sample's content of these metals concurs with the glass production technology during the sample's date (the 16th century AD or later) (Gratuze et al. 1995).

The white decorations of samples 3,11 and 14 contain dissolved tin oxide 1.28%, 7.22% and 0.88%, respectively. Backscattered electron microscope showed also tin oxide particles dispersed in the glass matrix. The presence of tin oxide (SnO_2) in the soda-lime-silica glass melt produced the white opaque glass, see spectrum 399 of sample 3 in Table 3. Few spot analyses of sample 3 have zinc in different concentrations which might indicate the use of brass alloys as well. It is probable that the white color resulted from the addition of lead tin calx (a residue formed when metals are heated together, Fig. 6, spectrum 312, lamp shape), where SnO_2 remains stable at temperatures above 750°C in the glass melt, while PbO remains stable at lower temperatures by the formation of yellow dispersed lead stannate crystals (Tite et al. 2008; Biron and Verita 2012).

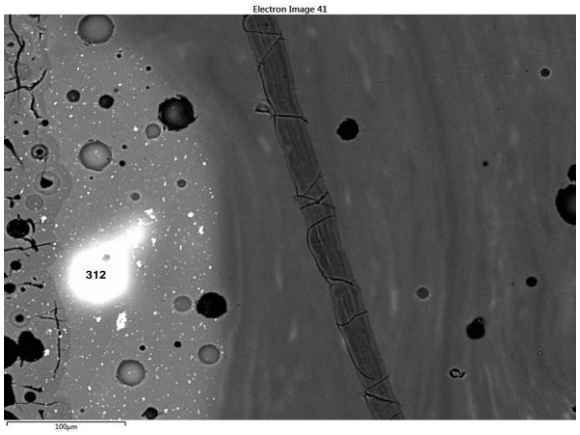


Fig. 6 A backscatter electron image of white color decoration of sample 3 from Umm el-Jimal showing elevated amounts of tin-lead particles (spectrum 312).

Table 3 shows differences in the concentrations of the metals present in the decorations; however, images of backscattered electrons show that the distribution of the added metals to most samples is inhomogeneous. Fig. 7 shows lighter areas with elevated concentrations of metal oxides and small metal particles nearly dissolved in the glass melt. On the contrary, darker areas have lower concentrations of these oxides and particles.

Spot analyses of a random group of bright particles in the yellow decorations of samples 4 and 14 (Table 3, Fig. 8) identify them as being lead–tin yellow, most likely $PbSnO_3$ (type II), with associated silica content (Gill and Rehren 2011; 2014). This conclusion is confirmed by the composition of the $PbSnO_3$ of samples 4 and 14 which has amounts of PbO of about 62.56-67.47%, SnO_2 of about 25.28-30.11% and silica (SiO_2 substituted SnO_2) in variable amounts of about 5.9-8.7%.

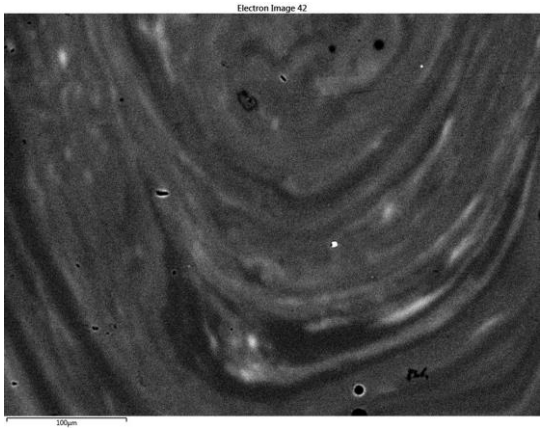


Fig. 7 A backscatter electron image of a blue color from sample 3 from Umm el-Jimal showing disseminated metals in the matrix and higher concentrations of metal oxides in the light areas than those of the dark areas (spectrums 319-330).

In antiquity, yellow opaque glass was produced by the addition of antimony or tin to a lead glass which causes the precipitation of yellow lead antimonate ($Pb_2Sb_2O_7$) or lead stannates ($Pb_2Sn_2O_4$ or $PbSnO_3$) (Henderson 1985). Antimony-based opacifiers were used by Roman glassmakers until the fourth century AD and were afterward gradually replaced by tin-based opacifiers (Tite et al. 2008; Verita et al. 2013). This chronological development might be used, but cautiously, to appraise the date of the yellow decorations; therefore, it is probable that they were produced after the fourth century when tin replaced antimony opacifier. The lemon yellow color of sample 4 only has dissolved tin dioxide (2.27%) and lead oxide (19.47%) indicating that lead-tin yellow (lead stannate $PbSnO_3$) is the colorant and opacifier used in this sample. On the contrary, the yellow decoration of sample 14 has lower concentrations of dissolved lead and dispersed lead stannate particles. Because the matrices of yellow decorations of the rest of samples (3 and 11) do not contain tin or antimony, it is likely that the yellow decoration was produced from iron oxide Fe(III) by controlling the amount of oxygen present in the furnace or making use of the presence of other redox systems in the batch such as manganese ions (see above).

The yellow decorations of sample 11 have high values of manganese oxide 3.29 and 3.50% and Mn/Fe ratios of 5.37 and 3.99, while sample 14 contains 0.9% of manganese oxide, 0.56% of iron, 6.11% of lead oxide and Mn/Fe ratio of 1.59 (Mirti et al. 2002; Silvestri et al. 2005). Because an equilibrium between the yellow ferric ion (Fe^{3+}) and the blue ferrous ion, Fe^{2+} iron exsists in the glass, Fe^{3+} should predominate in order to color the glass yellow. The manganese functions as an oxidizing agent of Fe^{2+} iron to Fe^{3+} iron; thus, produces the yellow color (Scott et al. 2006). In addition, sample 11 has more lead than sample 14; consequently, it is probable that more yellow lead sannates precipitated in sample 11 than sample 14 which increased the intensity of its yellow color (Mirti et al. 2002).

The green threads of sample 1 contain copper (average =1.42%) and high amounts of lead and tin, while the yellowish green threads lack copper and has lower amounts of lead and tin than the green one. It is most likely that the green opaque decoration is formed due to the suspension of lead-tin crystals in the copper rich matrix, while the lead and tin crystals in the absence of copper caused the yellowish green hue (Freestone et al. 1990, Meulebroeck et al. 2010).

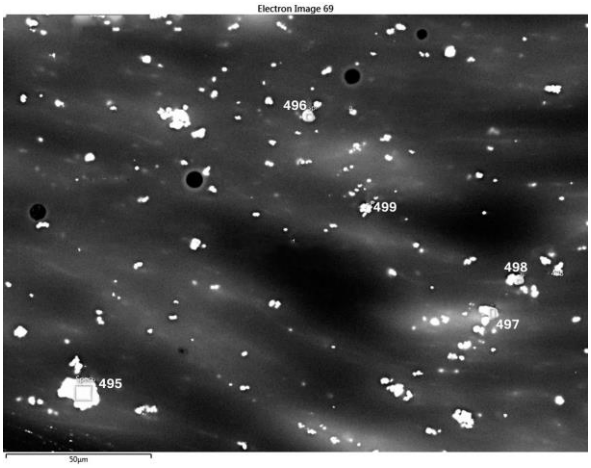


Fig. 8 A backscatter electron image of yellow color decoration of sample 14 from Umm el-Jimal showing elevated amounts of lead-tin-silica (PbSnO) particles (Spectrums 495-499).

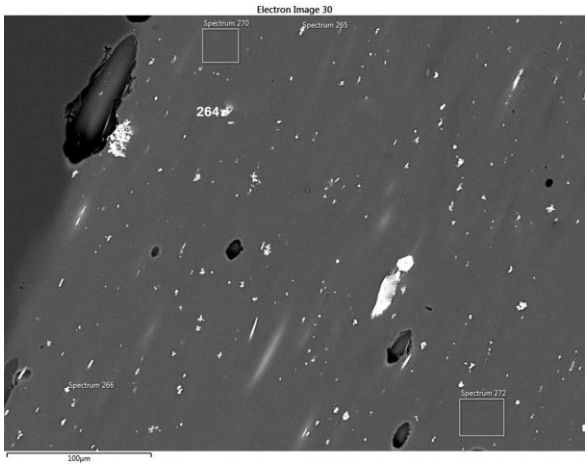


Fig. 9 A backscatter electron image of blue color decoration of sample 2 from Umm el-Jimal showing disseminated tin oxide particles (Spectrum 264).

Light and deep colored greenish blue hues of sample 2 have different compositions (Table 3). The high CuO content (2.7%) and Cu/Fe ratio (5.2) most likely rendered the glass blue (Mirti et al. 2002). On the contrary, the deeply colored greenish blue hue lacks copper; therefore, it is likely that this color was obtained from reduced iron oxide Fe(II) in the presence of lead and tin oxides (Fig. 9).

5. CONCLUSIONS

Although the studied fragments have doubtful dates, a combined approach of stylistic and chemical analyses indicates that the bracelets were most probably Islamic and made of plant-ash (11 samples), natron (5 samples), mixed natron-plant ash (3 samples) glasses and one mineral glass (sample 3). The composition of bracelets accords with the trend of changes of glass technology happened during the Roman-Islamic periods. They show plant-ash glass which replaced the natron glass during the ninth

century AD and the use of tin oxide and manganese oxide that replaced antimony oxide at the end of the fourth century AD. However, glassmakers followed earlier production traditions including the production of green and blue colors using copper and iron and the recycling of old colored glass (such as opaque mosaic tessera as explained by Theophilus (Hawthorne and Smith, 1963) and shown by several studies; for example Freestone (1993); Wolf et al. (2005); Al-Bashaireh et al. (2016). The black appearance of some samples resulted from the deliberate addition of high values of iron oxide and manganese or increased thickness of other bracelets having low values of these elements. Furthermore, glassmakers of this period used pure metal flakes of a hammer scale that resembles an artificial by-product of metal working as a source of glass colorant.

ACKNOWLEDGEMENTS

I would like to thank the Department of Antiquities, Jordan for their permission to collect the samples and Dr. Abdul-Qader Al-Housan, the director of Al-Mafraq Directorate of Antiquities for providing the samples and his guidance. I acknowledge the University College London at Doha, Qatar for providing me the fellowship to visit, use and analyze the samples in their archaeometry laboratories. I would like to thank Dr. Myrto Georgakopoulou and Mr. Philip Connolly for their guidance and help in analyzing the samples. I thank Professor Ian Freestone for reading and commenting on the paper.

REFERENCES

Aerts, A., Janssens, K., Velde, B., Adams, F., and Wouters, H. (2000) Analysis of the composition of glass objects from Qumrân, Israel, and comparison with other Roman glass from western Europe. *Travaux de la Maison de l'Orient méditerranéen,* 33, 113-121.

Ahmed, AA. and Ashour, GM. (1981) Effect of heat treatment on the crystallization of cuprous oxide in glass. Glass technology 22(1): 24-33

Al-Bashaireh, K. (2014) Reconstructing the chronology of the house XVII-XVIII complex at Umm El-Jimal, east Jordan: radiocarbon dates of organic inclusions of architectural mortars. *Radiocarbon* 56, 1: 245-256.

Al-Bashaireh, K., Freestone IC., Al-Mustafa, Sh.; Al-Housan, A-Q., (2016) Composition of Byzantine glasses from Umm el-Jimal, northeast Jordan: Insights into glass origins and recycling. *Journal of Cultural Heritage,* 21(5): 809-818.

Arletti, R., Fiori, C. and Vandini, M. (2010) A study of glass tesserae from mosaics in the monasteries of Daphni and Hosios Loukas (Greece). *Archaeometry* 52: 796-815.

Barber, DJ., Freestone, IC. and Moulding, KM. (2009) Ancient copper red glasses: investigation and analysis by microbeam techniques. In: Shortland A J, Freestone IC, Rehren Th (eds) From mine to microscope: Advances in the study of ancient technology. Oxbow, Oxford, pp. 115-127.

Biron, I. and Verità, M. (2012) Analytical investigation on Renaissance Venetian enameled glasses from the Louvre collections. *Journal of Archaeological Science* 39,8: 2706-2713.

Boulogne, S. (2008) Les bracelets de verre coloré polychromes des sites de Damas, Masyaf, Tell Abû Sarbût et Hirbat fâris au Bilâd al-Châm mamelouk et ottoman: essai de synthèse. *Bulletin d'Études Orientales* 17: 127-154.

Boulogne, S. and Hardy-Guilbert, C. (2010) Glass bangles of al-Shiḥr, Ḥaḍramawt (fourteenth-nineteenth centuries), a corpus of new data for the understanding of glass bangle manufacture in Yemen. In Starkey J (ed.), *Proceedings of the seminar for Arabian studies*, vol. 40. Archaeopress, Oxford, pp. 135-148.

Boulogne, S. and Henderson, J. (2009) Indian glass in the Near-East? Medieval and Ottoman glass bangles from central Jordan. *Journal of Glass Studies* 51: 53–75.

Brill, RH. (1999) *Cemical analyses of early glass.* The Corning Museum of Glass, New York.

Brill, RH. and Cahill, ND. (1988) A red opaque glass from Sardis and some thoughts on red opaque in general. *Journal of Glass Studies* 30: 16-27.

Bugoi, R., Poll, I., Manucu-Adamesteanu, Gh., Neelmeijer, C. and Eder, F. (2013) Investigation of Byzantine glass bracelets from Nufaru, Romania using external PIXE-PIGE methods, Journal of Archaeological Science, vol. 40, 2881-2891.

Cagno, S., Cosyns, P., Van der Linden, V., Schalm, O., Izmer, A., Deconinck, I., Vanhaecke, F., Nowak, A., Wagner, B., Bulska, E., Nys, K. and Janssens, K. (2013) Composition data of a large collection of black-appearing Roman glass. *Open Journal of Archaeometry* 1,1:104-108.

Cagno, S., Cosyns, P., Izmer, A., Vanhaecke, F., Nys, K. and Janssens, K. (2014) Deeply colored and black-appearing Roman glass: a continued research. *Journal of Archaeological Science* 42: 128-139.

Cholakova, A. and Rehren, Th. (2014) Producing black glass during the Roman period–notes on a crucible fragment from Serdica, Bulgaria. In Scott R, Braekmans M, Degryse P (eds.) *Proceedings of the 39th International Symposium for Archaeometry*. Centre for Archaeological Sciences, Leuven, pp. 261-267.

De Vries, B. (1993) The Umm el-Jimal Project, 1981-1992. *Annual of the Department of Antiquities of Jordan* 37: 433-460.

De Vries, B. (1994) What's in a name: the anonymity of ancient Umm el-Jimal. *Biblical Archaeology* 57(4): 215-219.

De Vries, B. (1998) *Umm el-Jimal: a frontier town and its landscape in northern Jordan*. Vol. 1. Rhode, Island Portsmouth.

Dussart, O., Velde, B., Blanc, P.M. and Sodini, J.P. (2004) Glass from Qal'at Sem'an (Northern Syria): the re-working of glass during the transition from Roman to Islamic composition. *Journal of Glass Studies* 46: 67-83.

Fiori, C. (2015) Production technology of Byzantine red mosaic glasses. Ceramics Internatgional 41(2): 3152-3157.

Foster, H. and Jackson, CM. (2009) The composition of 'naturally coloured' late Roman vessel glass from Britain and the implications for models of glass production and supply. *Journal of Archaeological Science* 36**:** 189-204.

Freestone, IC. (1987) Compositions and microstructure of early opaque red glass. In Bimson M, Freestone I (eds) *Early vitreous materials*. British Museum Occasional Paper 56, London, pp. 173–191.

Freestone, IC. (1993) Compositions and origins of glasses from Romanesque champleve enamels. In Stratford N. (ed.), *Catalogue of Medieval Enamels in the British Museum*. Vol. II, Northern Romanesque Enamel. British Museum Press, London, pp. 37-45.

Freestone, IC., Bimson, M. and Buckton, D. (1990) Compositional categories of Byzantine glass tesserae. *Annales du 15e`me Congre`s de l'Association Internationale pour l'Histoire du Verre*: AIHV, New York-Corning, pp.271-281.

Freestone, IC., Gorin-Rosen, Y. and Hughes, MJ. (2000) Primary glass from Israel and the production of glass in late antiquity and the early Islamic period. *Travaux de la Maison de l'Orient méditerranéen* (33): 65-83.

Freestone, I., Ponting, M. and Hughes, M. (2002a) The origins of Byzantine glass from Maroni Petrera, Cyprus. *Archaeometry* 44 (2): 257-272.

Freestone, I., Greenwood, R. and Gorin-Rosen, Y. (2002b) Byzantine and early Islamic glassmaking in the Eastern Mediterranean: production and distribution of primary glass. In Kordas, G. (ed.), Hyalos - Vitrum - Glass. History, technology and conservation of glass and vitreous materials in the Hellenic World. *1st International conference Rhodes - Greece* 1-4 April 2001. Athens, pp.167-174.

Freestone, IC., Stapleton, CP. and Rigby, V. (2003) The production of red glass and enamel in the Later Iron Age, Roman and Byzantine periods. In Entwistle C (ed.) *Through a glass brightly-studies in Byzantine and Medieval Art and Archaeology presented to David Buckton*. Oxbow, Oxford, pp.142-154.

Freestone, IC., Jackson-Tal, RE., Taxel, I. and Tal, O. (2015) Glass production at an Early Islamic workshop in Tel Aviv. *Journal of Archaeological Science* 62**:** 45-54.

Ganio, M., Boyen, S., Fenn, T., Scott, R., Vanhoutte, S., Gimeno, D. and Degryse, P. (2012) Roman glass across the Empire: an elemental and isotopic characterization. *Journal of Analytical Atomic Spectrometry* 27(5): 743-753.

Gill, MS. and Rehren, Th. (2011) Material characterization of ceramic tile mosaic from two 17th century Islamic monuments in northern India. *Archaeometry* 53(1): 22-36.

Gill, MS. and Rehren, Th. (2014) The intentional use of Lead–Tin orange in Indian Islamic glazes and its preliminary characterization. *Archaeometry* 56(6): 1009-1023.

Goffer, Z. (2007) *Archaeological chemistry*. Vol. 170. John Wiley and Sons, New Jersey.

Gratuze, B., Soulier, I., Barrandon, JN. and Foy, D. (1995) The origin of cobalt blue pigments in French glass from the thirteenth to the eighteenth centuries. In Hook DR, Gaimster DRM (eds.) *Trade and Discovery: The Scientific Study of Artefacts from Post- Medieval Europe and Beyond.* British Museum Ocaasional Paper N. 109. British Museum Press, London, pp. 123-133.

Hawthorne, JG. and Smith, CS. (1963) *On Divers Arts: The Foremost Medieval Treatise on Painting, Glassmaking, and Metalwork.* Dover publication, New York.

Henderson, J. (1985) The raw materials of early glass production. *Oxford Journal of Archaeology* 4,2: 267-291.

Henderson, J. (1991) Industrial specialization in late Iron Age Britain and Europe. *Archaeological Journal* 148,1: 104-148.

Henderson, J. (2002) Tradition and experiment in 1st millennium AD glass production – the emergence of Early Islamic Glass technology in late antiquity. *Accounts of Chemical Research* 35: 594-602.

Henderson, J. (2006) *Ancient glass: an interdisciplinary exploration.* Cambridge University Press, Cambridge.

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

Kuisma-Kursula, P. (2000) Accuracy, Precision and Detection Limits of SEM–WDS, SEM–EDS and PIXE in the Multi-Elemental Analysis of Medieval Glass. *X-Ray Spectrometry* 29**:** 111–118.

Lauwers, V., Degryse, P. and Waelkens, M. (2010) Middle Byzantine (10th-13th century A.D.) glass bracelets at Sagalassos (SW Turkey). In Drauschke J, Keller D (eds.) *Glass in Byzantium-Production, Usage, Analyses. RGZM e Tagungen, Band 8.* Verlag des Römisch-Germanischen Zentralmuseums, Mainz, pp. 145-152.

Meulebroeck, W., Baert, K., Wouters, H., Cosyns, P., Ceglia, A., Cagno, S., Janssens, K., Nys, K., Terryn, H. and Thienpont, H. (2010) The identification of chromophores in ancient glass by the use of UV-VIS-NIR spectroscopy. In Berghmans F, Mignani A G, Van Hoof CA (eds.) *Proceedings SPIE Photonics Europe.* 7726(77260D): 1-13.

Meyer, C. (1992) *Glass from Quseir el-Qadim and the Indian Ocean Trade.* The Oriental Institute of the University of Chicago, Chicago.

Mirti, P., Davit, P., Gulmini, M. and Saguì, L. (2001) Glass fragments from the Crypta Balbi in Rome: the composition of eighth-century fragments. *Archaeometry* 43(4): 491-502.

Mirti, P., Davit, P. and Gulmini, M. (2002) Colourants and opacifiers in seventh and eighth century glass investigated by spectroscopic techniques. *Analytical and Bioanalytical Chemistry* 372: 221–9.

Peake, JR. and Freestone, IC. (2012) Cross-craft interactions between metal and glass working: slag additions to early Anglo-Saxon red glass. In Meulebroeck W, Nys K and Vanclooster D (eds) *Integrated Approaches to the Study of Historical Glass*-IAS12. 8422(842204): 1-12.

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

Ram, A., Prasad, SN., Srivastava, KP. and Prasad, SS. (1970) On the role of Tin in Copper ruby glass. *Transactions of the Indian Ceramic Society* 29(2): 35-40.

Rehren, Th., Marii, F., Schibille, N., Stanford, L. and Swann, C. (2010) Glass supply and circulation in early Byzantine southern Jordan. In Drauschke J, Keller D (eds.) *Glass in Byzantium-Production, Usage, Analyses. RGZM e Tagungen, Band 8.* Verlag des Römisch-Germanischen Zentralmuseums, Mainz, pp. 65–81.

Rehren, T., Cholakova, A. and Zivanovi, C.M. (2012) The making of black glass in Late Roman Doclea, Montenegro. *New Antique Doclea* 3(7): 71-90.

Schibille, N. and Freestone, IC. (2013) Composition, production and procurement of glass at San Vincenzo al Volturno: an early Medieval monastic complex in southern Italy. *PloS one* 8(10): e76479.

Shortland, A. J., Schachner, L., Freestone, I. C. and Tite, M. (2006) Natron as a flux in the early vitreous materials industry - sources, beginnings and reasons for decline. *Journal of Archaeological Science* 33(4): 521-530

Silvestri, A., Molin, G. and Salviulo, G. (2005) Roman and medieval glass from the Italian area: Bulk characterization and relationships with production technology. *Archaeometry* 47(4): 797-816

Silvestri, A. and Marcante, A. (2011) The glass of Nagora (Verona): a "window" of production technology of mid-Medieval times in Northern Italy, Journal of Archaeological Science, vol. 38, 2509-2522.

Spaer, M. (1988) The Pre-Islamic glass bracelets of Palestine. *Journal of Glass Studies* 30: 51-61

Spaer, M. (1992) The Islamic glass bracelets of Palestine: preliminary findings. *Journal of Glass Studies* 34: 44-62

Spaer, M. (2001) *Ancient glass in the Israel Museum: beads and other small objects.* Israel Museum, Jerusalem.

Steiner, ML. (2008) An analysis of the Islamic glass bracelets found at Tell Abu Sarbut. In Steiner ML. and van der Steen EJ (eds.) *Sacred and Sweet; Studies in the Material Culture of Tell Deir `Alla and Tell Abu Sarbut*. Peeters, Leuven, pp. 231-240.

Tal, O., Jackson-Tal, RE. and Freestone, IC. 2004 New evidence of the production of raw glass at late Byzantine Apollonia-Arsuf, Israel. *Journal of Glass Studies* 46: 51-66.

Tal, O., Jackson-Tal R. E. and Freestone, I. C. (2008) Glass from a Late Byzantine secondary workshop at Ramla (south), Israel. *Journal of Glass Studies* 50: 81-95.

Tite, M., Pradell, T. and Shortland, A. (2008) Discovery, production and use of Tin-based opacifiers in glasses, enamels and glazes from the Late Iron Age onwards. *Archaeometry* 50(1): 67-84

Uboldi, G. and Verta, M. (2003) Scientific analyses of glasses from Late Antique and Early Medieval archaeological sites in northern Italy. *Journal of Glass Studies* 45: 115-137

Van der Linden, V., Cosyns, P., Schalm, O., Cagno, S., Nys, K., Janssens, K., Nowak, A., Wagner, B. and Bulska, E. (2009) Deeply coloured and black glass in the northern provinces of the Roman Empire: differences and similarities in chemical composition before and after ad 150. *Archaeometry* 51(5): 822-844

Verità, M., Maggetti, M., Saguì L. and Santopadre, P. (2013) Colors of Roman glass: an investigation of the yellow sectilia in the Gorga collection. *Journal of Glass Studies* 55: 39-52.

Walker, BJ., Kenney, E., Holzweg, L., Carroll, L. and Boulogne, S., Lucke, B. (2007) Village life in Mamluk and Ottoman HubrāB and Sa'Ham: Northern Jordan Project, Report on the 2006 Season. *Annual of the Department of Antiquities of Jordan* 52: 429–470.

Wolf, S., Kessler, CM., Stern, WB. and Gerber, Y. (2005) The composition and manufacture of early medieval coloured window glass from Sion (Valais, Switzerland)da Roman glass-making tradition or innovative craftsmanship? *Archaeometry* 47: 361-380.

Young, T. (2011) Some preliminary observations on hammer scale and its implications for understanding welding. *Historical Metallurgy* 45(1): 26-41.