

## BYZANTINE OPAQUE RED GLASS TESSERAE FROM BELT SHEAN, ISRAEL\*

A. N. SHUGAR

*Institute of Archaeology, University College London, 31-34 Gordon Square, London, WC1H 0PY, UK*

*This paper presents the results of analysis of Byzantine opaque red glass tesserae derived from three separate locations in the ancient city of Beit Shean, Israel. Investigation proceeded using reflective light microscopy, energy dispersive X-ray fluorescence and energy dispersive scanning electron microscopy. The glass matrix of the tesserae was found to be heterogeneous, with many inclusions. Similarities and differences between tesserae from the two mosaics are examined and discussed. Implications for locale of manufacture and production techniques are considered. Comparisons between the three locations led to conclusions about the use of the tunnel as a storage site and the implications of this for future research on mosaics.*

**KEYWORDS:** ISRAEL, BEIT SHEAN, BYZANTINE, ENERGY DISPERSIVE SCANNING ELECTRON MICROSCOPY, ENERGY DISPERSIVE X-RAY FLUORESCENCE, REFLECTIVE LIGHT MICROSCOPY, MOSAICS, TESSERAE, GLASS, OPAQUE RED, COMPOSITION, MANUFACTURE, PROVENANCE

### INTRODUCTION

Antique opaque red glass has been extensively analysed and discussed (Bimson 1987; Brill and Cahill 1988; Cable and Smedley 1987; Freestone 1987; Freestone *et al.* 1992; Henderson 1991a and 1991c; Hughes 1972; Mallowan 1954; Turner 1956). However, analysis and interpretation relating specifically to mosaic glass tesserae has been limited. Most papers have focused on the formation and production of similarly coloured enamels (Henderson 1991a and 1991c; Hughes 1972). Although Freestone *et al.* (1992) do focus on the analysis of Byzantine tesserae, the underlying objective was to study Byzantine enamels.

Chemical compositional investigations of ancient opaque red glass as well as modern attempts to reproduce it have shown that the usual colouring agent is copper based, typically cuprite (Ahmed and Ashour 1981; Brill and Cahill 1988; Cable and Smedley 1987; Duran *et al.* 1984; Duran and Valle 1985; Freestone 1987; Hughes 1972; Weyl 1959). Opaque red glass is perhaps the most difficult glass to produce, as reported in the literature (Bimson 1987; Brill and Cahill 1988; Henderson 1991a; Hughes 1972) and as personally confirmed in experimental replication (in 1997, unpubl. report available on request). In view of this difficulty, it is likely that the craftsmen were extremely specialized and that production in the region was limited to a few glass factories. Because of their value, tesserae would most likely have been preserved and reused as much as possible and it is almost certain that opaque red tesserae were not recycled as cullet (Freestone *et al.* 1992). This is known to have been the case with vessel glass of the period. Opaque red glass was specifically chosen for this study because of its rarity and because it is an

\* Received 26 April 1999, accepted 9 September 1999.

excellent indicator of sophisticated technology in antiquity (Bimson 1987; Brill 1991; Brill and Cahill 1988; Henderson 1991a and 1991c; Sanderson and Hutchings 1987).

This report presents the results of scientific examination and analysis of opaque red mosaic glass tesserae from the ancient Byzantine city of Beit Shean, Israel (Bar-Nathan and Mazor 1993). Beit Shean is located at the crossroads of the four largest and most important cities of the time, Jerusalem, Damascus, Amman and the port of Acco, and it is considered to have been the most important trade centre for these cities. The glass was recovered from three separate locations within the city. Two of the locations, an apse in the north-west corner of the large bathhouse (AK 61193) and the western apse of the exedra (EK 60223), are well dated through contextual association with pottery and coins. Indeed, inscriptions at these two locations provide their exact dates of construction as CE 507 (the exedra) and CE 535 (the bathhouse). While this by no means dates the production of the tesserae, it does indicate that the tesserae were installed during these construction periods. The tesserae recovered in a third location, a tunnel within a smaller bathhouse (GK 100746), have also been dated by associated pottery and coins and are estimated to have been deposited sometime in the seventh century CE (W. Atrash, pers. comm. 1994). Atrash and consulting excavators have interpreted this location as a storage facility for tesserae destined for reuse. This conclusion was reached on the basis of the large quantities of tesserae found, *en masse* and undisturbed (c. 95 litres, 12 buckets), and the wide variety in colour (all primary and secondary colours in several shades, and clear). Additionally, the attached plaster had come from a flat surface, not the curved surface of the tunnel walls. The inside of a tunnel is, anyway, an unlikely location for a glass mosaic, which depends on the reflection of ambient light for its brilliance (L'Orange and Nordhagen 1966). The location, inside a dry tunnel thought to connect both sides of the city, would, however, have been ideal for storage, providing access for reuse of the tesserae on both sides of the city. The findings also suggest that the glass had been stored where it was found prior to the deposition of the comparative dating materials.

The literature contains only a small number of quantitative chemical analyses of Byzantine opaque red glass tesserae. Freestone *et al.* (1992) reported six samples, one from Shikmona, Israel, four from Hosios Loukas, northern Greece, and one from San Marco, Venice. Brill and Cahill (1988) reported one sample from St. Demetrius, Thessaloniki, and one from San Clemente, Rome. These eight samples derive from five sites across the Mediterranean and range in date from the fifth century CE to c. CE 1130. The present study extends these analyses with 20 additional samples from the three separate locations in one city. The analyses allow us to speculate about the production techniques of the tesserae used in the mosaics and to provide insight into the possible reuse of tesserae within this city.

#### SAMPLING

During excavation of the three locations at Beit Shean, approximately 117 litres (16 buckets) of glass tesserae were found, containing c. 100 opaque red pieces (all tesserae were subsequently stored on site). The 100 pieces were of uniform red colour and opacity. 20 specimens of opaque red glass for the present analysis, six from the exedra, and seven from each of the other two locations (the bathhouse and the tunnel), were selected by simple random sampling. These samples were analysed for chemical composition and microstructure using optical microscopy, energy dispersive X-ray fluorescence (ED-XRF) at the Department of Archaeology, Durham University, and energy dispersive scanning electron microscopy (ED-SEM) at the Ancient Monuments Laboratory, London.

## METHOD OF ANALYSIS

Sections were sampled from each tessera with a diamond blade and mounted in epoxy resin. The exposed surfaces were ground on successive grades of grinding paper from 400 to 2500 grit and polished with diamond paste at 6, 3, 1 and 0.25 micron. All effects of weathering were removed in the process.

Each sample was inspected visually for colour and final colour determination was done optically, comparing samples to a HEX triplet colour chart. Subsequently each sample was examined under a Nikon Optiphot-2 reflective optical microscope to determine the degree of heterogeneity and the size, numbers and types of inclusions, and photographed. Scanning electron microscopy was used to confirm heterogeneity and diversity.

Next, ED-XRF was used to determine the general chemical composition of each sample. This analysis was carried out in vacuum on a Link 200 ED-XRF. The fundamental parameters for the Link 200 were adjusted using a Corning 'A' glass standard. A copper drift standard was used at ten sample intervals to ensure minimal detector drift. A 2 mm collimator was used to produce an oval spot size of 3 mm by 5 mm. Eighteen elements were looked for-Si, Ca, Na, Mg, K, Al, Cu, Fe, Pb, Mn, Sn, P, S, Ti, Sb, Cl, Zn and As-and amounts were calculated as oxides. Data collection was performed with a Link EDS with live time set at 100 seconds at 20 keV. Minimum detection levels were calculated between a low of 0.003% for iron and a high of 1.18% for sulphur. In six samples the totals for all elements measured fell below 95%, probably because the samples were smaller than the spot size.

## RESULTS

*Visual colour matching and reflective light microscopy*

The colours of all the samples were identified as either 990000 or BB0000 (two almost identical reds) on the Hex Triplet colour chart. All samples showed identical features under the optical microscope, the most notable of which was the extremely heterogeneous nature of the glass. This heterogeneity was seen as striations and strands, stones and extensive inclusions spread throughout the glass matrix. Stones were present in the form of devitrified glass and a variety of crystalline structures, which tended to be spindle or lath shaped. Other inclusions identifiable as copper prills and iron ranged from 0.25 micron to 4 mm in size. The red colouring agent in the tesserae was crystalline cuprous oxide (cuprite). The cuprite was finely dispersed in a generally homogeneous pattern, with higher concentrations forming the waves and striations noted under optical microscopy. These striations and strands produced more intense colour and greater opacity in the glass. These optical observations were confirmed by SEM.

*Chemical composition by ED-XRF*

The chemical compositions of the base glass of the tesserae from all three locations are typical for their period and provenance (Sayre and Smith 1961; Weinberg 1988) (see Table 1). They are a soda-lime-silica glass with composition comparable to other opaque red tesserae analysed from Israel (Freestone *et al.* 1992). Levels of potassium are at the upper end of the low range as defined by Sayre and Smith (1961). On ED-XRF, the detection limit for magnesium was 0.9 wt%. Sixteen of the samples analysed were below this limit and four were above the limit, ranging from 0.94 to 1.44 wt%, but all fell within the low range as defined by Sayre and Smith.

Table I Chemical composition of opaque red glass tesserae from Beit Shean, Israel (ED-XRF)

		<i>Sampl</i>	<i>SiO<sub>2</sub></i>	<i>Na<sub>2</sub>O</i>	<i>CaO</i>	<i>K<sub>2</sub>O</i>	<i>MgO</i>	<i>Al<sub>2</sub>O<sub>3</sub></i>	<i>MnO</i>	<i>CuO</i>	<i>PbO</i>	<i>Fe<sub>2</sub>O<sub>3</sub></i>	<i>TiO<sub>2</sub></i>	<i>P<sub>2</sub>O<sub>5</sub></i>	<i>ZnO</i>	<i>SnO</i>	<i>Cl</i>	<i>SO<sub>2</sub></i>	<i>Sb<sub>2</sub>O<sub>5</sub></i>	<i>As<sub>2</sub>O<sub>3</sub></i>	<i>Total</i>
Bathhouse	1	61193	63.95	13.57	8.19	1.66	nd	3.51	0.54	1.07	2.71	3.23	0.07	0.05	nd	0.89	0.25	0.32	nd	nd	80.74
	2	61193	62.97	11.81	9.25	1.77	nd	4.13	0.59	1.25	3.25	3.44	0.10	0.07	nd	0.82	0.28	0.27	nd	nd	101.23
	3	61193	62.13	10.76	9.67	1.85	nd	4.19	0.67	1.64	3.78	3.77	0.12	0.06	nd	1.14	0.23	nd	nd	nd	68.49
	5	61193	62.09	11.46	9.26	1.81	0.94	4.24	0.66	1.25	3.36	3.42	0.09	0.06	nd	0.71	0.26	0.39	nd	nd	96.95
	6	61193	61.05	11.18	8.86	1.68	nd	3.82	0.61	1.42	3.18	7.07	0.08	0.07	nd	0.71	0.27	nd	nd	nd	95.72
	7	61193	64.10	11.45	8.92	1.60	nd	4.51	0.58	1.04	3.41	3.12	0.06	0.06	nd	0.82	0.34	nd	nd	nd	86.22
Exedra	8	60223	55.86	15.29	7.23	1.45	nd	3.13	0.89	2.53	6.39	2.50	0.18	1.16	1.75	0.64	0.34	0.67	nd	nd	100.98
	9	60223	57.82	16.14	7.33	1.16	nd	3.02	1.10	1.51	5.28	2.04	0.13	0.97	1.63	0.72	0.24	0.91	nd	nd	96.42
	10	60223	56.48	14.60	7.34	1.44	nd	3.50	0.90	2.01	6.32	2.71	0.17	1.16	1.79	0.56	0.33	0.68	nd	nd	100.25
	11	60223	56.85	15.78	7.54	1.37	1.27	3.24	0.55	1.64	5.21	2.19	0.19	0.86	1.30	0.75	0.39	0.86	nd	nd	103.03
Tunnel	12	60223	56.41	15.83	7.63	0.96	nd	3.30	0.61	1.96	5.87	2.51	0.22	1.01	1.85	0.77	0.30	0.78	nd	nd	99.28
	13	60223	56.42	16.56	7.27	1.32	1.44	3.62	0.53	1.58	4.99	2.12	0.18	0.82	1.26	0.73	0.40	0.74	nd	nd	103.51
	14	100147	63.52	14.67	8.30	0.86	nd	3.75	0.13	1.89	0.62	4.67	0.09	nd	nd	0.92	0.16	0.43	nd	nd	89.03
	15	100147	59.57	13.41	9.05	0.91	nd	3.77	0.39	1.38	5.41	4.64	0.08	0.02	nd	0.94	nd	0.44	nd	nd	82.58
Tunnel	16	100147	58.99	14.10	8.16	0.88	0.92	4.21	0.75	1.61	2.55	4.79	0.11	0.37	1.29	0.84	nd	0.41	nd	nd	102.89
	17	100147	57.54	14.60	8.09	1.15	nd	3.76	1.51	1.53	5.05	2.18	0.17	0.98	1.51	0.69	0.36	0.87	nd	nd	96.17
	18	100147	59.02	15.10	7.87	0.92	nd	4.03	1.18	1.72	3.64	2.98	0.13	0.59	1.45	0.75	0.02	0.58	nd	nd	97.53
	19	100147	62.06	13.41	9.79	0.74	nd	4.28	0.29	1.11	4.17	3.16	0.08	nd	nd	0.67	0.24	nd	nd	nd	89.23
	20	100147	58.87	15.02	8.46	0.78	nd	4.00	0.36	1.12	6.35	3.50	0.08	nd	nd	0.89	0.19	0.37	nd	nd	98.38

Values are normalized for comparison, totals are original; nd: not detected.

Sample 6 high iron content due to a piece of iron in the section.

(1961) and Henderson (1991a, 1991b and 1991c). Copper, the colourant, is present in levels between 1.04 and 2.53 wt% which is comparable to other Byzantine glass tesserae analysed (Brill and Cahill 1988; Freestone *et al.* 1992).

## INTERPRETATION AND DISCUSSION

### *Similarities between three locations*

In each of the three locations there are distinct differences in the chemical composition of the tesserae. This is confirmed by analysis of variance (see Table 2). Both the bathhouse and the exedra have very tight groupings for all elements while the tunnel varies widely in both additives and base glass. This base glass is typical of late Byzantine and early Roman glass production in the Near East and fits well into the prescribed context. Although they all fall within the broader range established for Byzantine glass of this period, each of the three locations has separate and distinctly different base glass compositions. The levels of Si, Ca, Na, Al, Mg and K are all within the reported ranges of other analysed Byzantine and Roman tesserae (Brill and Cahill 1988; Freestone *et al.* 1992; Henderson 1991a) and confirm earlier reports. The consistency in the proportions of the major elements and the levels of trace elements in the tesserae from the three locations indicate the probable use of similar raw materials. The elements used as intentional additives were all easily accessible to glassmakers in the ancient Near East during this period.

When the content of SiO<sub>2</sub> is plotted against the content of PbO the spreads from the three sites indicate that the tesserae from the exedra and the bathhouse fall into two distinct and separate clusters, whereas those from the tunnel spread more widely, overlapping with the other two clusters (Fig. 1). Analysis of all the elements confirms this impression by revealing clear differences in the glass from the three settings. Boxplots (Fig. 2) are used to illustrate these differences.

Table 2 Oneway ANOVA  
between all three groups

	<i>F</i>	<i>Sig.</i>
SiO <sub>2</sub>	27.77	.000
Na <sub>2</sub> O	41.071	.000
CaO	19.003	.000
K <sub>2</sub> O	63.049	.000
Al <sub>2</sub> O <sub>3</sub>	14.408	.000
MnO	0.368	.698
CuO	6.796	.007
PbO	6.764	.007
Fe <sub>2</sub> O <sub>3</sub>	4.772	.023
TiO <sub>2</sub>	19.917	.000
ZnO	25.917	.000
SnO	18.625	.000
Cl	2.316	.129
P <sub>2</sub> O <sub>5</sub>	7.894	.004
SO <sub>3</sub>	15.193	.000

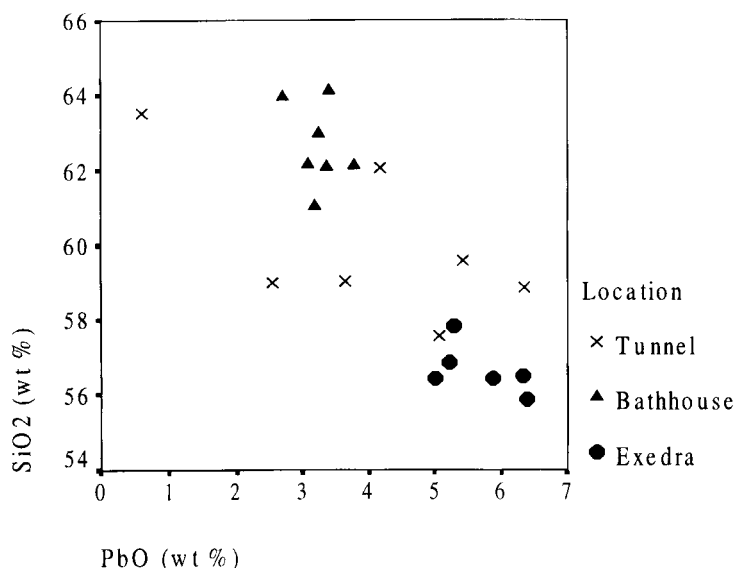


Figure 1 Spread of SiO<sub>2</sub> to PbO for the three locations.

#### *Comparison of the tesserae found at the bathhouse and the exedra*

For 14 of the 16 elements detected in tesserae from the bathhouse and exedra, boxplot analysis shows distinct, tight groupings for all samples from each location, but obvious differences when one location is compared with the other. In each case, the range of findings in the tunnel overlaps the values from both the exedra and the bathhouse (see Fig. 2). Of the two exceptions, one element, MgO, was below detection limits and the other, P<sub>2</sub>O<sub>5</sub>, was not distinctly different for the three locations.

The significance of the difference between the means was analysed using independent t-tests (see Table 3). For 12 of 15 elements within the detection limits, means were significantly different, with p values ranging from .000 to .018. The other three were marginally significant, with p values ranging from .083 to .108. This confirms the initial impressions conveyed by the boxplots. However, while the differences are significant, the means are not widely disparate for most elements.

The relative consistency of the base glass and the tight groupings of each mosaic's additives are best explained by concluding that the tesserae from each location were produced with the same formula but in different batches, which would be expected from two sites 28 years apart in construction. These findings also suggest that production was probably standardized during the period in which these tesserae were produced and that a formula for producing an opaque red glass was well established and available to affiliated glassmakers. This would be consistent with an established manufacturing industry in the region. It is likely that red tesserae, being difficult to manufacture and relatively rarely used, would have been produced both for local consumption and for extended trade. Based on the large size and strategic economic location of the city, it is also a strong possibility that production was based in Beit Shean. With Beit Shean being a major trading centre of the time, the precious opaque red glass could easily have been distributed to the surrounding major centres. Some support for this conclusion may derive from the finding of a

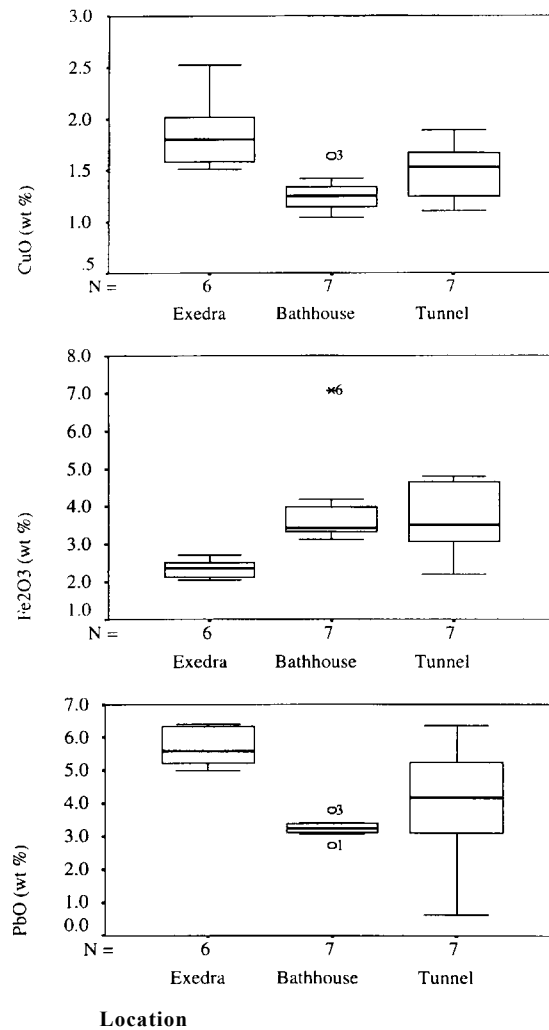


Figure 2 Boxplot analysis of opaque red glass tesserae from the three locations.

vessel glass workshop located in Beit Shean during the 1994-5 excavation season (Mazor and Bar-Nathan 1998, 27-9), although glassworking and glassmaking are not necessarily linked.

#### *Differences between the tesserae from the bathhouse and the exedra*

There are two distinct differences between the two sets of tesserae from the exedra and the bathhouse. The first is the 16-fold difference in ZnO levels and the second is the presence of tin in the chronologically earlier location (exedra) and its absence in the later location (bathhouse).

The elevated levels of ZnO in the tesserae from the exedra show a strong correlation to CuO, PbO and SnO. While it is possible that the increase in ZnO could derive from the addition of either brass or gun metal to the melt, it is more likely that the increase in ZnO can be attributed to

Table 3 Comparison of elements from the exedra (seven samples) and the bathhouse (six samples)

	Group statistics				t-test for equality of means	
	Means		Standard deviation		t	p =
	Exedra	Bathhouse	Exedra	Bathhouse		
SiO <sub>2</sub>	62.6335	56.6391	1.1013	0.6586	11.63	0
Na <sub>2</sub> O	11.8118	15.701	0.9375	0.6818	-8.41	0
CaO	9.0506	7.3924	0.4634	0.1598	8.31	0
K <sub>2</sub> O	1.7348	1.2821	8.97E-01	0.1898	5.65	0
Al <sub>2</sub> O <sub>3</sub>	4.0319	3.3028	0.3347	0.2266	4.51	0.001
MnO	0.6095	0.7646	4.43E-01	0.2313	-1.75	0.108
CuO	1.2714	1.8739	0.2047	0.3795	-3.64	0.004
PbO	3.2539	5.6783	0.3272	0.6003	-9.24	0
FeO <sub>3</sub>	4.0333	2.3449	1.3863	0.2651	2.92	0.014
TiO <sub>2</sub>	8.90E-01	0.1803	1.91E-01	2.86E-01	-6.87	0
ZnO	6.13E-01	0.9972	7.79E-02	0.1421	-17.52	0
SnO	0	1.5967	0	0.2559	-16.63	0
Cl	0.828	0.6942	0.1552	7.86E-01	1.9	0.083
P <sub>2</sub> O <sub>5</sub>	0.2812	0.3318	4.31E-01	5.82E-01	-1.8	0.099
SO <sub>3</sub>	0.1809	0.7746	0.1737	9.75E-01	-7.4	0

the increase in both CuO and PbO (Pearson correlation coefficients .809 and .774 respectively,  $p = .01$  and .01). Tin-zinc bearing ores are extremely rare, if they occur at all, while copper-zinc and lead-zinc ores are common and abundant (Craig and Vaughan 1994).

Although tin plays an active role in deoxidizing and improving a melt, Cable and Smedley (1987) note that the absence of tin from a glass batch has little if any effect on the end result when an opaque red glass is produced. It is possible that tin was not available to the manufacturer at the time of production for the bathhouse (Freestone *et al.* 1992, 278). Higher demand by metalsmiths at the time may also contribute to its absence. With reference to opaque red glass in general, there are a number of possible ways tin may be introduced into the melt. Brill and Cahill (1988) have suggested that tin could have been introduced in the form of bronze scaling. This would lead to the expectation that the general ratio of tin to copper in the glass would correspond to the ratio in the bronze (c. 5-30%) However, in the tesserae analysed here, the ratio of tin is well above that range and is almost identical to the levels of copper suggesting that tin was an intentional additive.

#### *Relation of the tesserae from the tunnel to those from the exedra and the bathhouse*

In the tesserae from the tunnel, tin was present in three samples and absent in four. Where tin was present it was comparable to the levels found in the exedra tesserae. The tesserae with no tin are consistent with those found in the bathhouse. In the tesserae from the exedra and the bathhouse the groupings for all five elements measured (Pb, Fe, Cu, Mn, Zn) are extremely tight. The corresponding values for the tunnel have a relatively wide spread. This spread encompasses the values from both other locations, and is wider than would be expected if the tesserae in the tunnel derived from a single source or were manufactured in a single batch. Statistical comparison of 14 elements in the tunnel samples with those in the two other locations, individually or combined (t-test), shows no significant differences in the mean values for any element. Of the seven tesserae



samples located in the tunnel, numbers 17 and 18 match most closely with the tesserae from the exedra, whereas number 19 matches most closely with the tesserae from the bathhouse. Although number 16 has comparable tin levels, the increased amount of  $\text{Fe}_2\text{O}_3$  and decreased amount of  $\text{PbO}$  exclude it from the exedra grouping. The other tesserae, numbers 14, 15 and 20, show some similarities to the other two groups in base glass, but, again, have enough difference in  $\text{Fe}_2\text{O}_3$  and  $\text{PbO}$  to be excluded from the other groupings. Since these samples match neither the bathhouse nor the exedra, they may have derived from other mosaics located around the site and been placed in the tunnel to store for reuse. The comparison of the tesserae in the tunnel with the tesserae in the bathhouse and the exedra supports the conclusion that the tunnel was a storage facility for tesserae reclaimed for reuse. One may conclude that the tunnel probably contained the products of more than one batch.

### CONCLUSIONS

Because of their relative rarity and the difficulty involved in their production, antique opaque red glass tesserae are a unique and informative material for study. The originality of the present study lies in its investigation of glass tesserae from three locations within one site, dated over a relatively short time-span. There are few analyses of tesserae in the literature, fewer of opaque red tesserae and none of tesserae from multiple locations within one site. In addition, this is the first report on tesserae from Beit Shean.

The glass matrix of the tesserae was found to be heterogeneous, with many inclusions of various compositions. Chemical compositional analysis determined that the base glass of the tesserae conformed to compositional trends seen in other contemporary late Roman and Byzantine glasses. Additives in the glass were found to cluster in tight groups for the tesserae from the bathhouse and the exedra, while the tesserae from the tunnel had wider variations, overlapping the other two. These results imply that the glasses in the former locations derive from individual single batches while the tesserae from the tunnel are a collection of more than one batch and may even contain some of the tesserae from the first two locations.

Based on these findings, it is likely that the tesserae from all three locations were produced from a standardized formula, possibly in a factory in the city of Beit Shean itself. The base glasses for the tesserae from the bathhouse and exedra are clearly different and  $\text{SnO}$  is only used in the earlier mosaic, indicating they derive from separate batches. Although it is possible that the differences in the two batches reflect manufacture in two different factories, it is more likely that manufacture occurred in a single factory and the differences reflect relatively small changes in the use of materials over time. This view is preferable since so few of these specialized factories are expected to have existed.

The tunnel is interpreted as being a storage facility for tesserae reclaimed for recycling and supporting evidence is provided. This should alert future investigators to the possibility that tesserae collected from a single mosaic can derive from either a single batch or from multiple sources if they were stored and reused.

### ACKNOWLEDGEMENTS

I would like to thank G. Mazor and R. Bar-Nathan of the Israeli Antiquity Authority for providing the samples and for their encouragement. I would also like to thank Dr C. Jackson, Dr I. Freestone and Dr G. Shugar for their insightful comments in reviewing this manuscript.

## REFERENCES

- Ahmed, A. A., and Ashour, G. M., 1981, Effect of heat treatment on the crystallization of cuprous oxide in glass, *Glass Technol.*, **22**, 24-33.
- Bar-Nathan, R., and Mazor, G., 1993, Beit Shean, in *Excavations and surveys in Israel* (eds. D. Sussman and N. Silberstein), 33-52, Israeli Antiquities Authority, Jerusalem.
- Bimson, M., 1987, Opaque red glass: a review, in Bimson and Freestone 1987, 165-71.
- Bimson, M., and Freestone, I. C., 1987, *Early vitreous materials*, British Mus. Occas. Pap., **56**, London.
- Brill, R. H., 1991, Scientific investigation of some glasses from Sedeinga, *J. Glass Stud.*, **33**, 11-29.
- Brill, R. H., and Cahill, N. D., 1988, A red opaque glass from Sardis and some *thoughts* on red opaques in general, *J. Glass Stud.*, **30**, 16-27.
- Cable, M., and Smedley, J. W., 1987, The replication of an opaque red glass from Nimrud, in Bimson and Freestone 1987, 151-64.
- Craig, J. R., and Vaughan, D. J., 1994, *Ore microscopy and ore petrography*, John Wiley & Sons, Toronto.
- Duran, A., Fernandez-Navarro, J. M., Garcia Sol, J., and Agullo-Lopez, F., 1984, Study of the colouring process in copper ruby glass by optical and ESR spectroscopy, *J. Material Sci.*, **19**, 1468-76.
- Duran, A., and Valle, F. G., 1985, Analysis of the different states of oxidation of copper in glasses: redox equilibrium, *Glass Technol.*, **26**, 179-85.
- Freestone, I. C., 1987, Composition and microstructure of early opaque red glass, in Bimson and Freestone 1987, 173-91.
- Freestone, I. C., Bimson, M., and Buckton, D., 1992, Compositional categories of Byzantine glass tesserae, *Annales 12<sup>e</sup> congrès de l'Association internationale pour l'histoire de la verrerie*, 271-81, AIHV, Amsterdam.
- Henderson, J., 1991a, Chemical characterization of Roman glass vessels, enamels and tesserae, in *Materials issues in art and archaeology II* (eds. P. B. Vandiver, J. Druzik and G. S. Wheeler), 601-7, Materials Res. Soc. Symposium Proc., **185**, Pittsburgh.
- Henderson, J., 1991b, Industrial specialisation in Late Iron Age Britain and Europe, *Archaeol. J.*, **148**, 104-48.
- Henderson, J., 1991c, Technological characterizations of Roman enamels, *Jewellery Stud.*, **5**, 65-76.
- Hughes, M. J., 1972, A technical study of opaque red glass in the Iron Age in Britain, *Proc. Prehist. Soc.*, **38**, 98-107.
- L'Orange, H. P., and Nordhagen, P. J., 1966, *Mosaics*, Methuen & Co. Ltd, London.
- Mallowan, M. E. L., 1954, The excavations at Nimrud (Kalhu), 1953, *Iraq*, **16**, 59-163.
- Mazor, G., and Bar-Nathan, R., 1998, The Bet She'an excavation project-] 992-1994, *Excavations and Surveys in Israel*, **17**, 7-38.
- Rothenberg, B., 1985, Copper smelting furnaces in the Arabah, Israel: the archaeological evidence on furnaces and smelting technology in antiquity, in *Furnace and smelting technology in antiquity, London 1982* (eds. P. T. Craddock and M. J. Hughes), 123-50, British Mus. Occas. Pap., **48**, London.
- Sanderson, D. C. W., and Hutchings, J. B., 1987, The origins and measurement of colour in archaeological glasses, *Glass Technol.*, **28**, 99-195.
- Sayre, E. V., and Smith, R. W., 1961, Compositional categories of ancient glass, *Science*, **133**, 1824-6.
- Turner, W. E. S., 1956, Ancient sealing-wax red glasses, *J. Egyptian Archaeol.*, **43**, 110-12.
- Weinberg, G., 1988, *Excavations at Jalame: site of a glass factory in late Roman Palestine*, Univ. Missouri Press, Columbia.
- Weyl, W. A., 1959, *Coloured glasses*, Dawson's of Pall Mall, London.