Received: 25 March 2023 | Accepted: 12 October 2023

DOI: 10.1111/arcm.12929

ORIGINAL ARTICLE

Composition and affinities of glass from the Ma'agan Mikhael B shipwreck, Israel

Agnese Benzonelli[1,2] | Eyal Natan[2] | Yael Gorin-Rosen[3] | Ian C. Freestone[4]

[1]McDonald Institute for Archaeological Research, University of Cambridge, Cambridge, UK

[2]UCL Institute of Archaeology, London, UK

[3]Department of Maritime Civilisations, University of Haifa, Haifa, Israel

[4]Glass Department, Israel Antiquities Authority, Jerusalem, Israel

Correspondence
Agnese Benzonelli, McDonald Institute for Archaeological Research, University of Cambridge, Cambridge, UK.
Email: ab2852@cam.ac.uk

Funding information
Israel Science Foundation, Grant/Award Number: 1891/16; Honor Frost Foundation; Institute of Nautical Archaeology (INA); Texas A&M University, Grant/Award Number: 039; University of Haifa

Abstract
Material recovered from the Ma'agan Mikhael B shipwreck, off the coast of northern Israel, includes a significant assemblage of glass, which appears to represent waste workshop material (cullet) collected for recycling. Twenty-three samples were selected for analysis for major and minor elements using SEM-EDS, to provide insight into the activities and dating of the ship. The glass corresponds to known primary glass types, comprising a high- and a low-lime subgroup of Levantine 1 (Apollonia type), and Egypt 1b. The assemblage is likely to date to the early part of the eighth century CE and, in conjunction with the radiocarbon dating of the ship, gives a possible date range for the wreck of 710–740 C.E. All groups contain glass-working waste, glass chunks, and vessel fragments, and the majority are likely to have been collected from one or more workshops. It is unclear whether this cargo represents the byproducts of several campaigns of a single workshop which used different consignments of raw glass, or material from different workshops, collected at different ports of call.

KEYWORDS
early Islamic, maritime trade, Natron glass, recycling, shipwreck

INTRODUCTION

The Ma'agan Mikhael B shipwreck is located some 35 km south of Haifa, 70 m off the coast and at a depth of 3 m. Excavations have revealed the well-preserved remnant of a 25 m long merchantman with a cargo carried in amphorae originating from various regions, including Egypt and Cyprus (Creisher et al., 2019). The wreck has been dated to the mid-seventh–mid-eighth centuries CE (Cohen & Cvikel, 2018; Creisher et al., 2019). More than 870 glass fragments were found in the ship, concentrated in the area between the mast step and the fore bulkhead, comprising chunks of glass, moils, vessels (e.g., bowls, bottles, and wine glasses), and oil lamps, most dating to the Late Byzantine and early Islamic periods in the region (for further discussion of the glass finds, see elsewhere: Natan et al., 2021). Although other glass cargos have been found off the coast of Israel (Galili et al., 2015), the Ma'agan Mikhael B assemblage is important because it was discovered within the confines of the ancient vessel, indicating that it represents a single cargo.

The number of complete glass vessels retrieved was low, and the presence of glass and glass production waste, as well as broken vessels, suggests that the glass assemblage largely represents a cargo of cullet, intended to be unloaded for remelting at some port of call (Natan et al., 2021). The present compositional analysis was carried out to determine the compositional affiliations of the glass in the cargo, with a view to determining its origin and to provide more information on the context of the wreck, the activities of the ship, as well as offering some interesting possibilities for future investigations.

MATERIALS AND METHODS

The glass was fully sorted and categorised based upon typology and fabric as part of an MA project (Natan, 2020). Samples, selected to be representative of the assemblage, were removed from 23 objects, shown in Figure 1. Brief descriptions are provided in Table 1. They are from three stages of production:

1. Glass chunks. The purpose of analysing the findings from this group is to examine the composition and characteristics of the materials from which the glass was made, and to locate the region and even the factory of origin. The following samples belong to this group (sample numbers according to Table 1, below): 4, large brown glass chunk; 5, dark green; 7, greenish; 8, colourless with purplish tinge; 16, yellowish green; 23, dark green glass.
2. Fragments of dated glassware. The vast majority of the vessels were dated to the late Byzantine and early Islamic periods, presented by samples: 3, 12, 13, 14, 19, 20, 21, and 24. One vessel is dated to the late Roman period presented by Sample 2. In addition, two mosaic tesserae were also chosen, Samples 15 and 18.
3. Glass production debris. These samples include 6, moil (blowing leftover); 10, glass attached to the furnace wall; sample 22, glass chunk with attached furnace material; and two glass drops, samples 11, 17.

Analysis was undertaken in the Wolfson Laboratories of the Institute of Archaeology, London. Samples were prepared as cross-sections in epoxy resin and polished to a 1 μm finish, then vacuum coated with carbon. Analyses were performed using a Zeiss EVO 25 scanning electron microscope and fitted with an Oxford Instruments AZTEC energy dispersive X-ray spectrometer. Operating conditions were 20 kV acceleration potential and an acquisition time of 100 s. Pure elements and oxides were used to standardise the analyses, whereas a cobalt metal standard was used to correct for instrumental drift. Results are calculated with oxygen by stoichiometry and totals normalised to 100%. Unless indicated, the values reported are the means of five individual measurements. Corning A and B were analysed as reference standards (Table 2), and results indicate relative errors better than 5% for most elements present in concentrations above 1 weight % absolute, with accuracy declining as limits of detection were approached. Measured alumina contents were low in both standards, so for the purpose of

FIGURE 1 Photos of the samples analysed.

comparison with published compositions, an empirical correction of 6% relative was applied to bring the data in line with Corning B, which has the Al_2O_3 content closest to the archaeological samples (Table 2). Although use of the uncorrected data would not modify the conclusions of this paper, when used in Figure 2 the adjusted alumina demonstrates a more probable juxtaposition of the new and reference data. However, the values presented in Table 2 are the original, uncorrected values.

RESULTS

The glass groups

Results are presented in Table 2. Apart from a contaminated ceramic furnace fragment, all the samples analysed are soda-lime silica glasses, typically with low K_2O and MgO below 1.5%, and therefore made using natron, characteristic of the Roman, Byzantine, and early Islamic

TABLE 1 Description of the samples analysed.

Sample no.	Figure no.	Basket no.	Type and period
2	1	455	Bowl, late Roman
3	4	408	Wine glass, Late Byzantine
4	12	404	Glass chunk
5	13	455/1	Glass chunk
6	17	455/2	Moil
7	15	452	Glass chunk
8	16	425/1	Glass chunk
10a	20	407/1a	Glass chunk with furnace debris
10b	21	407/1b	Glass chip
11	18	407/2	Glass drop
12	2	422	Wine glass, Late Byzantine
13	8	422	Bottle with applied wavy trail, Late Byzantine-Umayyad
14	9	445	Handle, oil lamp, Late Byzantine
15	10	427	Tesserae
16	14	425/2	Glass chunk
17	19	425/3	Glass drop
18	11	455	Tesserae
19	6	442	Bottle with infolded rim, Late Byzantine-Umayyad
20	7	442	Bottle with infolded rim, Late Byzantine-Umayyad
21	3	453	Wine glass, Late Byzantine
22	22a	425/4a	Glass chunk with furnace debris
23	22b	425/4b	Glass chunk
24	5	425/5	Deformed wine glass

periods (Table 2). Natron glass of the first millennium CE can be grouped into around 10 main types based upon major elemental composition and taking excavated production sites into consideration (Foy et al., 2003; Freestone, 2020a; Freestone et al., 2000; Schibille et al., 2019). These can be discriminated by their oxides of titanium, aluminium, and silicon (Freestone, 2020a, 2020b; Freestone et al., 2018), with soda and lime as useful additional discriminants (Al-Bashaireh et al., 2016; Barfod et al., 2018; Phelps et al., 2016).

In terms of the characteristic sand components (Figure 2), the glasses correspond to three compositional types. The majority are generally grouped under the umbrella 'Levantine I', and in the present case are closest to those produced by the furnaces at Apollonia, which operated in the sixth–seventh centuries (Freestone, 2020b; Freestone et al., 2000, 2008; Tal et al., 2004).

One sample (7, a chunk) lies slightly above the others, with higher TiO_2/Al_2O_3 (Figure 2); however, it also has slightly elevated FeO, so that its TiO_2/FeO ratio is typical of Apollonia-type glass, and it is assumed it is a piece of raw glass with a higher heavy mineral content, which has not been diluted by mixing with more representative Apollonia material in a secondary melting process. It could however, be the result of recycling Levantine glass with a higher TiO_2 type such as Foy 2.1.

The second group corresponds to 'Egypt 1' glass (Gratuze & Barrandon, 1990), specifically Egypt 1b, as defined by Schibille et al. (2019). In addition to the components incorporated in Figure 2, these glasses have the relatively high Na_2O, FeO, and MgO characteristic of Egypt

TABLE 2 SEM-EDS analyses.

Sample	Description	Na2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	ClO	K_2O	CaO	TiO_2	MnO	FeO	Type
18	Tesserae, light green tint	17.8	0.57	1.79	70.1	<0.1	0.42	1.11	0.38	6.24	0.10	0.87	0.64	Foy 3.2
2	Bowl with folded collar	13.5	0.54	2.70	72.1	0.08	0.12	0.98	0.80	8.78	0.08	<0.1	0.39	Apollonia
3	Wine glass, solid stem	14.6	0.54	2.93	73.9	<0.1	0.16	0.86	0.43	6.00	0.09	<0.1	0.44	Apollonia
4	Brown chunk	13.7	0.5	3.17	73.7	<0.1	0.11	0.88	0.50	6.93	0.09	<0.1	0.47	Apollonia
7	Glass chunk green	14.1	0.9	2.69	69.0	<0.1	0.18	1.01	0.56	8.88	0.13	1.95	0.61	Apollonia
8	Chunk, colourless + purple streaks	13.9	0.73	2.99	67.9	0.1	0.17	0.91	0.65	9.48	0.11	2.45	0.56	Apollonia
11	Melted drop bluish	15.4	0.54	2.95	69.5	<0.1	0.30	0.84	0.56	9.43	0.08	<0.1	0.41	Apollonia
13	Bottle with wavy trail decoration	15.4	0.58	3.13	71.8	<0.1	0.14	0.89	0.57	6.96	0.08	<0.1	0.47	Apollonia
15	Tesserae, yellowish	13.5	0.76	2.96	66.2	0.13	0.23	0.71	0.80	10.09	0.12	3.76	0.76	Apollonia
17	Waste drop, blue	11.2	0.55	2.94	69.7	<0.1	0.13	0.86	4.48	9.60	0.08	<0.1	0.42	Apollonia
19	Lt blue bottle, folded rim	13.9	0.55	2.95	71.0	0.12	0.16	0.81	0.86	9.14	0.09	<0.1	0.43	Apollonia
21	Lt blue wine glass with hollow base	15.1	0.52	3.35	71.5	<0.1	0.18	1.00	0.53	7.20	0.10	<0.1	0.51	Apollonia
24	Deformed solid stem, lamp or wine glass	14.2	0.45	3.02	72.5	<0.1	0.25	0.89	0.93	7.26	0.08	<0.1	0.38	Apollonia
12	Lt blue wine glass, hollow base	17.3	0.57	3.10	68.2	<0.1	0.40	0.93	0.57	8.41	0.07	<0.1	0.37	Levantine 1
5	Chunk, dark green	16.9	0.81	3.98	71.1	<0.1	0.24	1.10	0.46	3.15	0.52	<0.1	1.7	Egypt 1
6	Moil	16.5	0.77	3.94	72.1	<0.1	0.10	1.18	0.53	2.84	0.51	<0.1	1.57	Egypt 1
10a	Furnace wall	16.9	1.20	4.63	65.0	<0.1	0.17	0.84	0.56	7.13	0.65	<0.1	2.91	Egypt 1
10b	Glass attached to 10a	17.4	0.81	3.96	70.2	<0.1	0.18	1.08	0.48	3.63	0.51	<0.1	1.77	Egypt 1
14	Green handle, oil lamp	18.4	0.78	3.74	70.5	<0.1	0.18	1.25	0.44	2.88	0.43	<0.1	1.46	Egypt 1
16	Chunk, dark yellowish green	17.5	0.79	3.92	71.1	<0.1	0.10	1.24	0.48	2.86	0.50	<0.1	1.58	Egypt 1
20	Dk green bottle with infolded rims	16.6	0.84	3.99	71.2	<0.1	0.14	1.08	0.50	3.17	0.60	0.06	1.82	Egypt 1
23	Same chunk (22) dark green glass	16.0	0.80	3.92	71.3	0.06	0.20	0.99	0.49	4.05	0.48	0.06	1.67	Egypt 1
22	Furnace waste on 23 (bulk analysis)	10.7	1.33	7.39	70.9	<0.1	0.37	0.43	0.72	4.17	0.90	<0.1	3.50	Waste
Corning A	Mean 5	14.2	2.58	0.90	66.6	0.08	0.2	0.09	2.95	5.09	0.83	1.06	1.10	Standard
Corning A	Accepted	14.3	2.66	1.00	66.6	0.13	0.14	0.09	2.87	5.03	0.79	1.00	0.98	Standard
Corning B	Mean 5	16.7	1.04	4.13	61.5	0.84	0.61	0.17	1.08	8.81	0.12	0.25	0.32	Standard
Corning B	Accepted	17.0	1.03	4.36	61.55	0.82	0.49	0.16	1.00	8.56	0.09	0.25	0.31	Standard

Each represents an average of 5 points. *Note*: 'Apollonia' refers to Levantine 1 glass which is compositionally close to the known products of the tank furnaces at Apollonia. The possibility of a similar production elsewhere in the region remains open at the present time. All glasses are translucent/transparent; dk, dark; lt, light. Accepted values for Corning Museum ancient glass standards from Brill (1999) as modified by Adlington (2017) for Cl, SO_3.

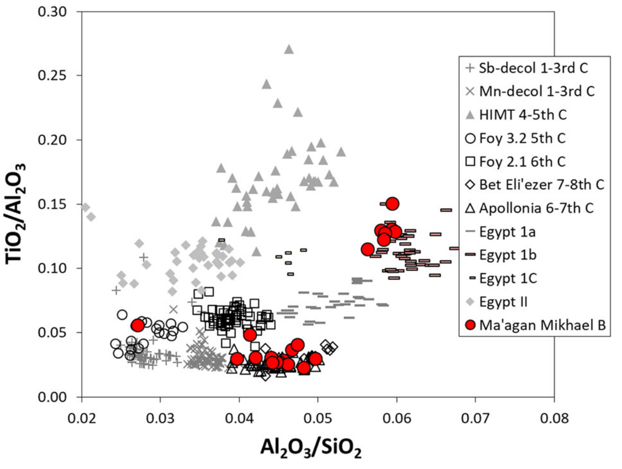

FIGURE 2 Glass from the Ma'agan Mikhael B compared with major known types from the first millennium CE. Reference data from Foy et al. (2003), Silvestri (2008), Silvestri et al. (2008), Schibille et al. (2019), and Freestone et al. (2015). An empirical correction of 6% relative was applied to bring the data relative to the Al_2O_3 in line with Corning B standard (see text).

1, with low CaO in the range 4%–5%. One sample is off scale in Figure 2; this is an Egyptian 1b glass contaminated by ceramic (sample 10b, Table 2). It has high Al_2O_3, FeO, and CaO but retains the high Na_2O characteristic of the original glass and is discussed further below.

Finally, a single sample (no. 18), a glass mosaic tessera, corresponds to Série 3.2 of Foy et al. (2003).

The compositional distinction between glass made in the three major Levantine production centres of Jalame (fourth century, Weinberg, 1988), Apollonia (sixth–seventh centuries, Tal et al., 2004), and Bet Eli'ezer (eighth century, Gorin-Rosen, 1995, 2000, for probable dating see also Phelps et al., 2016) is not straightforward as there are significant overlaps. All Levantine glass, produced from very similar coastal sand, has low TiO_2 and plots along the base of the graph in Figure 2. It appears that the Ma'agan Mikhael B glass best matches Apollonia, but there is a strong overlap with the later glass of Bet Eli'ezer in this diagram (Figure 2). However, CaO/Al_2O_3 and Na_2O/SiO_2 ratios show more clearly that the Levantine glass in the assemblage mostly corresponds to the Apollonia type (Figure 3).

There is a significant clustering of the Apollonia-type glass from the Ma'agan Mikhael B into two subgroups: high and low-CaO (Figure 3). Although contamination during recycling can result in enrichment in CaO in Apollonia-type glass (Barfod et al., 2022; Chen et al., 2021), the two groups are well separated, and this does not suggest a derivation of the high CaO from the lowvCaO type. Rather, the two groups are likely to represent different batches or campaigns of production. An outlier with low Na_2O (sample 17, Figure 2) also contains exceptionally high K_2O at 4.5% (Table 2). The sample is a fragment of production waste, and the high potash is likely to be due to contamination from the fuel due to prolonged exposure in the furnace (Paynter, 2008). A second outlier (sample 12) has the characteristically high Al_2O_3 of Apollonia-type glass but also has exceptionally high soda. Its origin is uncertain, and it is therefore designated as Levantine 1 in Table 2. This may be a piece of earlier Jalame-type glass, but glass from Jalame frequently contains MnO, whereas the failure to detect manganese in this sample is fully consistent with an attribution to Apollonia (where there is no evidence for the use of manganese as a decoloriser), as is the form (wine glass with hollow base), which is distinctively Byzantine. This vessel is unlikely to have been derived from the same campaigns of production as the two main Apollonia subgroups.

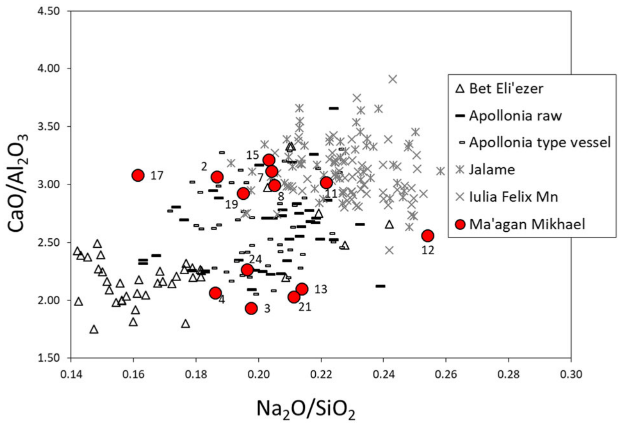

FIGURE 3 Ma'agan Mikhael B Levantine glass compared with major Levantine production centres and with Roman glass from the Iulia Felix wreck. There are two discrete clusters of Apollonia-type glass, with high and low calcium oxide. Reference data Jalame: Brill (1988), Iulia Felix: Silvestri (2008), Silvestri et al. (2008); Apollonia raw glass: Freestone et al. (2000, 2008), Tal et al. (2004); Apollonia-type vessel: Phelps et al. (2016); Bet Eli'ezer: Freestone et al. (2000 and unpublished).

The contaminated Egypt 1 glass

Two examples of Egypt 1 waste glass showed evidence of contamination from the furnace wall. Sample 10a was attached to a typical Egypt 1 glass (10b) but is enriched in CaO, MgO, and FeO (Table 2). This is similar to the type of contamination observed by Chen et al. (2021) in a Byzantine glass furnace, which had a CaO-rich lining, limiting interaction between the glass and the furnace.

One fragment comprised Egypt 1 glass juxtaposed against molten ceramic (samples 22, 23, Table 2). SEM examination of the ceramic revealed that it is likely to have been a mudbrick, tempered with quartz sand grains (Figure 4). Occasional lime-rich grains of a similar size to the quartz were identified and may represent calcareous sand grains. Alumina, lime, magnesia, and iron oxide contents are variably elevated relative to the typical Egypt 1 glass samples. A pyroxene phase, close to diopside in composition ($CaMgSi_2O_6$) has crystallised around and between the quartz particles. This suggests that the mud brick of the furnace wall was a quartz-tempered calcareous marl or clay. No evidence was found to confirm that the lime was added as a distinct layer, as suggested in Chen et al. (2021), although such an interpretation is possible. These observations may therefore be tentative evidence that lime-rich materials were preferred for furnace linings when Egypt 1 glass was being worked.

DISCUSSION

The Ma'agan Mikhael B assemblage comprises two main types of primary glass. The Apollonia-type was produced in Israel mainly in the sixth–seventh centuries. It is typically Byzantine, but Phelps et al. (2016) identify glass vessels in Israel with this composition going into the Umayyad and early Abbasid periods in the eighth century. According to Foy et al. (2003) Levantine-type glass containing manganese as a decolouriser does not occur after the fifth century, and certainly, manganese is not found in the raw glass of the primary furnaces at Apollonia. In the present case, added Mn occurs in three of the Levantine glasses analysed,

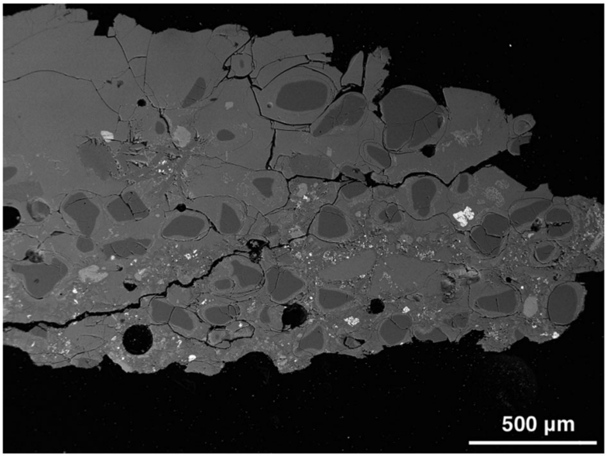

FIGURE 4 Cross section of Sample 22, showing glass (top) and molten furnace brick, which had been tempered with quartz sand (grey subrounded grains, bottom). The very bright areas are partially dissolved Fe-Ti oxides, whereas the light grey grains are lime-rich phases including diopsidic pyroxenes. Back-scattered electron image.

where it is present at levels around or above 2%, suggesting an intent to colour rather than decolourise the glass. The two clusters of Apollonia glass seen in Figure 3 are sufficiently discrete to have represented two separate campaigns of glass working, although there is no reason why these should not have occurred in the same workshop. The low-lime cluster is close to the compositions of glass from the eighth century furnaces at Bet Eli'ezer (Figure 2), however the soda contents do not match typical Bet Eli'ezer glass and are more consistent with Apollonia production.

The second major glass type from the ship is Egypt 1b, as defined by Schibille et al. (2019). Although it is considered to have been made in Egypt, where most samples have been identified (Foy et al., 2003; Gratuze & Barrandon, 1990; Kato et al., 2009), no production sites for Egypt 1 type glass have yet been located. Vessels in Egypt 1 glass have previously been identified in Israel (Phelps et al., 2016), but it is poorly represented comprising just two occurrences out of 133 well-dated vessels.

According to the survey of dated glass weights by Schibille et al. (2019) Egypt 1b was produced in 720–780 C.E. An allowance should be made for the possible continued use of glass stock in the production of the weights but even so, Egypt 1b is unlikely to have been produced before 710 C.E. Hence the occurrence of both Apollonia-type and Egypt 1b glass on the Ma'agan Mikhael B shipwreck corresponds very well with the archaeological dating of mid-seventh–mid-eighth centuries. Indeed, the juxtaposition of both glass types in significant proportions would suit a date in the early eighth century, when Apollonia production appears to have been replaced by Bet Eli'ezer (Phelps et al., 2016) and Egypt 1b was introduced. This is consistent with the radiocarbon dating of the wreck, which gives a range of 648–740 C.E. (94.5% probability; Cohen & Cvikel, 2018). Weighing these factors, a date for the ship of 710–740 C.E. would seem probable. The production of the anomalous Foy 3.2 glass would have been considerably earlier, in the fifth century (Cholakova & Rehren, 2018; Foy et al., 2003), but this is a mosaic tessera and is likely to have been collected specifically to be recycled from a mosaic under demolition.

In addition to glass vessels the assemblage analysed contains glass chunks and production waste, including glass with attached ceramic. Not only is there production waste and chunk glass among the Apollonia-type compositions but also in the Egypt 1b group (Table 1).

Furthermore, both high- and low-lime clusters of Apollonia glass contain vessels, production waste, and chunk glass (Table 1). Therefore, it appears that the assemblage comprises the waste material from one or more glass workshops, which was being transported for remelting.

The assemblage provides some insights into the character of glass recycling in the early Islamic period. The presence in the assemblage of glass waste, including moils and drops, as well as glass heavily contaminated with ceramic, suggests that whoever collected the cullet did not take care to exclude material that might contaminate the glass. Rather, anything that appeared glassy appears to have been salvaged. It seems likely that all would have been sorted in the secondary glass workshops and remelted to produce new batches of glass. The careful collection of all glassy material is likely to explain why the waste recovered from the excavation of glass-working sites is frequently quite sparse, as at the Byzantine workshop at 'Aqir, Israel (Chen et al., 2021). Given the proximity of the major primary glass producing sites, it is perhaps unexpected that so much attention was given to recycling, but there is significant compositional evidence for recycling in the region (e.g., Barfod et al., 2022; Freestone et al., 2008; Phelps et al., 2016).

The collection of apparently unsorted, sometimes contaminated glass material for recycling suggests that the glassworkers operated to tight margins so that fresh glass was expensive, even though it was made on a large scale in the region. From the perspective of compositional studies, the remelting of such an assemblage may have been an important pathway for contaminants such as iron, alumina, and lime to enter the batch.

The extent to which the glass analysis informs about the route of the Ma'agan Mikhael B shipwreck and its calling ports is debatable. Both types of glass identified were made in the region. Although finds of Egypt 1b glass are relatively uncommon in the area of modern Israel (Phelps et al., 2016), a later workshop at Tel Aviv appears to have worked both the succeeding primary glass type from Egypt, Egypt 2, as well as glass material made at Bet Eli'ezer (Hadera), which followed Apollonia as the main Levantine primary glassmaking centre (Freestone et al., 2015). The Ma'agan Mikhael B shipwreck may therefore have been carrying the material salvaged from a workshop situated in modern Israel, which had worked both Egyptian and Levantine glass. However, the analogy with the later material is not completely parallel because vessels made of Egypt 2 glass are a major part of the overall assemblage in Israel, far more common than Egypt 1b (Phelps et al., 2016). If a single workshop supplied the Ma'agan Mikhael B material and was located in Israel, its use of Egypt 1b would have been quite unusual. The alternative is that the ship was carrying material collected from more than one workshop, and that the Egypt 1b glass was obtained from a workshop located in Egypt. This would be consistent with the Egyptian amphorae in the cargo and would imply that the ship was sailing from south to north when it sank.

CONCLUSIONS

The analysis of glass from shipwrecks is informative, as it provides a snapshot of activity over a very short time span. As a cargo comprising a natron glass assemblage from secondary workshops, the Ma'agan Mikhael B is unusual and, as far as we are aware, the only assemblage of this type reported to date, with the famous Serçe Limanı wreck comprising later plant ash glass (Bass et al., 2009). Early Islamic workshop assemblages are unusual, but in the present case, recycling practices have provided several subassemblages, representing either a single workshop at different times or several workshops. The occurrence of both Levantine and Egyptian glass in the Ma'agan Mikhael B may suggest that, although raw glass was produced on a large scale in early Islamic Israel, some raw glass was imported from Egypt, which was then worked in a local workshop near the Israeli coast. However, the relatively small proportion of Egypt

1 vessels from the region so far analysed suggests that it was not imported in large amounts. Furthermore, the possibility that part of the glass cargo of the ship had been collected from a workshop in Egypt cannot be eliminated.

It seems quite possible that the ship represents an occasional barter trade on a small scale, tramping between traders in Egypt and Israel. Merchants would have collected local goods during a voyage along the coasts of Egypt and Israel (cabotage), which also included glass waste, collected while anchored in one of the ports close to glass workshops, such as Caesarea.

The presence of glass contaminated by furnace material suggests that the collection of material for remelting was not carefully controlled, and the glass workers were more concerned with the recovery of material than about minor amounts of contamination. As most of the glass was naturally tinted blue-green, attempts to eliminate contamination would not have been needed. This contrasts with some glass recycling activity in antiquity; for example, the integrity of recycled antimony-decolourised glass in the Roman period appears to have been carefully preserved in some circumstances (Freestone, 2015).

The precise dating of Islamic glass production achieved by the analysis of Egyptian coin weights (Schibille et al., 2019) has allowed us to offer a *terminus post quem* for the dating of the wreck that, in conjunction with the radiocarbon dating programme on the ship, places its likely occur within a 30-year timespan of 710–740 C.E.

ACKNOWLEDGEMENTS

The underwater excavations (IAA permits G-41/2016, G-40/2017, G-26/2018, G-34/2019, G-42/2021, and G-54/2022) and research of the Ma'agan Mikhael B shipwreck were supported by the Israel Science Foundation (grant no. 1891/16), the Honor Frost Foundation, the Institute of Nautical Archaeology (INA), Texas A&M University (grant no. 039), a Sir Maurice Hatter Fellowship, the President and Research Authority of the University of Haifa, Kibbutz Ma'agan Mikhael, and anonymous donors, to whom the authors are grateful. The authors would also like to thank Prof. Deborah Cvikel for allowing the authors to study and publish the material from the Ma'agan Mikhael B shipwreck.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are all included within this article.

ORCID

Agnese Benzonelli https://orcid.org/0000-0001-8282-9952

REFERENCES

Adlington, L. W. (2017). The Corning archaeological reference glasses: New values for "old" compositions. *Papers from the Institute of Archaeology*, *27*(1). https://doi.org/10.5334/pia-515

Al-Bashaireh, K., Al-Mustafa, S., Freestone, I. C., & 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*, 809–818. https://doi.org/10.1016/j.culher.2016.04.008

Barfod, G. H., Freestone, I. C., Jackson-Tal, R. E., Lichtenberger, A., & Raja, R. (2022). Exotic glass types and the intensity of recycling in the northwest quarter of Gerasa (Jerash, Jordan). *Journal of Archaeological Science*, *140*, 105546. https://doi.org/10.1016/j.jas.2022.105546

Barfod, G. H., Freestone, I. C., Lichtenberger, A., Raja, R., & Schwarzer, H. (2018). Geochemistry of Byzantine and Early Islamic glass from Jerash, Jordan: Typology, recycling, and provenance. *Geoarchaeology*, *33*(6), 623–640. https://doi.org/10.1002/gea.21684

Bass, G. F., Lledo, B., Matthews, S., & Brill, R. H. (2009). *Serçe Limani, Vol 2: The glass of an eleventh-century shipwreck*. College Station:Texas A&M University Press.

Brill, R. H. (1988). Scientific investigations of the Jalame glass and related finds. In G. D. Weinberg (Ed.), *Excavations at Jalame: Site of a glass factory in late Roman Palestine* (pp. 257–291). University of Missouri.

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

Chen, C., Freestone, I. C., Gorin-Rosen, Y., & Quinn, P. (2021). A glass workshop in 'Aqir, Israel and a new type of compositional contamination. *Journal of Archaeological Science: Reports*, *35*, 102786. https://doi.org/10.1016/j.jasrep.2020.102786

Cholakova, A., & Rehren, T. (2018). A late antique manganese decolourised glass composition: interpreting patterns and mechanisms of distribution. In D. Rosenow, M. Phelps, A. Meek, & I. Freestone (Eds.), *Things that travelled: Mediterranean glass in the first millennium AD* (pp. 46–71). UCL Press. https://doi.org/10.2307/j.ctt21c4tb3.9

Cohen, M., & Cvikel, D. (2018). Ma'agan Mikhael B, Israel: a preliminary report of a Late Byzantine–Early Islamic period shipwreck. *International Journal of Nautical Archaeology*, *48*(1), 189–207. https://doi.org/10.1111/1095-9270.12331

Creisher, M., Goren, Y., Artzy, M., & Cvikel, D. (2019). The amphorae of the Ma'agan Mikhael B shipwreck: Preliminary report. *Levant*, *51*(1), 105–120. https://doi.org/10.1080/00758914.2020.1723355

Foy, D., Picon, M., Vichy, M., & Thirion-Merle, V. (2003). Caractérisation des verres de la fin de l'Antiquitéen Méditerranée occidentale: l'emergence de nouveaux courants commerciaux. In D. Foy & M.-D. Nenna (Eds.), *Échanges et Commerce du Verre dans le Monde Antique* (pp. 41–85). Dremil-Lafage France: Éditions Monique Mergoil.

Freestone, I. C. (2015). The recycling and reuse of Roman glass: Analytical approaches. *Journal of Glass Studies*, 29–40.

Freestone, I. C. (2020a). Glass production in the first millennium CE: A compositional perspective. In F. Klimscha, H. J. Karlsen, S. Hansen, & J. Renn (Eds.), *Glas und Glasproduktion in Ur- und Frühgeschichtlicher Zeit*. Edition TOPOI.

Freestone, I. C. (2020b). Apollonia glass and its markets: An analytical perspective. In O. Tal (Ed.), *Apollonia-Arsuf: Final report of the excavations: Volume II: Excavations outside the Medieval town walls* (pp. 347–354). Tel Aviv: Tel Aviv University.

Freestone, I. C., Degryse, P., Lankton, J., Gratuze, B., & Schneider, J. (2018). HIMT, glass composition and commodity branding in the primary glass industry. In D. Rosenow, M. Phelps, A. Meek, & I. C. Freestone (Eds.), *Things that travelled: Mediterranean glass in the first millennium AD* (pp. 159–190). UCL Press. https://doi.org/10.2307/j.ctt21c4tb3.14

Freestone, I. C., Gorin-Rosen, Y., & Hughes, M. J. (2000). Primary glass from Israel and the production of glass in late antiquity and the early Islamic period. In M. D. Nenna (Ed.), *La Route Du Verre: Ateliers Primaires Et Secondaires Du Second Mil-lenaire Av. J.-C. Au Moyen Age* (pp. 65–83). Maison de l'Orient Mediterraneen.

Freestone, I. C., Jackson-Tal, R., & Tal, O. (2008). Raw glass and the production of glass vessels at late Byzantine Apollonia-Arsuf, Israel. *Journal of Glass Studies*, *50*, 67–80.

Freestone, I. C., Jackson-Tal, R., Tal, O., & Taxel, I. (2015). Glass production at an early Islamic workshop in Tel Aviv. *Journal of Archaeological Science*, *62*, 45–54.paynt. https://doi.org/10.1016/j.jas.2015.07.003

Galili, E., Gorin-Rosen, Y., & Rosen, B. (2015). Mediterranean coasts, cargoes of raw glass. *Hadashot Arkheologiyot Excavations and Surveys in Israel*, *127*. http://www.hadashot-esi.org.il/Report_Detail_Eng.aspx?id=24846&mag_id=122

Gorin-Rosen, Y. (1995). Hadera, Bet Eli'ezer. *Excavations and Surveys in Israel*, *13*, 42–43.

Gorin-Rosen, Y. (2000). The ancient glass industry in Israel: summary of the finds and new discoveries. In M.-D. Nenna (Ed.), *La Route Du Verre: Ateliers Primaires Et Secondaires Du Second Millenaire Av* (pp. 49–63). *J.-C. au Moyen Age*. Maison de l'Orient Mediterraneen.

Gratuze, B., & Barrandon, J. N. (1990). Islamic glass weights and stamps - analysis using nuclear techniques. *Archaeometry*, *32*, 155–162. https://doi.org/10.1111/j.1475-4754.1990.tb00462.x

Kato, N., Nakai, I., & Shindo, Y. (2009). Change in chemical composition of early Islamic glass excavated in Raya, Sinai peninsula, Egypt: On-site analyses using a portable X-ray fluorescence spectrometer. *Journal of Archaeological Science*, *36*, 1698–1707. https://doi.org/10.1016/j.jas.2009.03.020

Natan, E. (2020). *The glass finds from the Ma'agan Mikhael B Shipwrick*. [Unpublished Master's dissertation]. Department of Maritime Civilizations, Faculty of Humanities, University of Haifa.

Natan, E., Gorin-Rosen, Y., Benzonelli, A., & Cvikel, D. (2021). Maritime trade in early Islamic-period glass: New evidence from the Ma'agan Mikhael B shipwreck. *Journal of Archaeological Science: Reports 37*: 102903. https://doi.org/10.1016/j.jasrep.2021.102903

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

Phelps, M., Freestone, I. C., Gorin-Rosen, Y., & Gratuze, B. (2016). Natron glass production and supply in the late antique and early medieval near east: The effect of the Byzantine-Islamic transition. *Journal of Archaeological Science*, *75*, 57–71. https://doi.org/10.1016/j.jas.2016.08.006

Schibille, N., Gratuze, B., Ollivier, E., & Blondeau, É. (2019). Chronology of early Islamic glass compositions from Egypt. *Journal of Archaeological Science*, *104*, 10–18. https://doi.org/10.1016/j.jas.2019.02.001

Silvestri, A. (2008). The coloured glass of Iulia Felix. *Journal of Archaeological Science*, *35*, 1489–1501. https://doi.org/10.1016/j.jas.2007.10.014

Silvestri, A., Molin, G., & Salviulo, G. (2008). The colourless glass of Iulia Felix. *Journal of Archaeological Science*, *35*, 331–341. https://doi.org/10.1016/j.jas.2007.03.010

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

Weinberg, G. D. (1988). Excavations at Jalame: Site of a glass factory in late Roman Palestine. *Columbia*, 24–37.

How to cite this article: Benzonelli, A., Natan, E., Gorin-Rosen, Y., & Freestone, I. C. (2023). Composition and affinities of glass from the Ma'agan Mikhael B shipwreck, Israel. *Archaeometry*, 1–12. https://doi.org/10.1111/arcm.12929