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IN AN EARLIER publication, we presented an analysis of a raw glass furnace uncovered during excavations in the Byzantine city of Apollonia-Arsuf in 2002, and two additional raw glass furnaces found during excavations in 1950.[1] We suggested that the discovery of three raw glass furnaces at the site strengthens the assumption that the city was a major center for the making of both primary and secondary glass in the sixth and seventh centuries.[2] This article attempts to verify this assumption.

Apollonia-Arsuf is located on the Mediterranean coast of Israel, 17 kilometers north of Jaffa (Joppa, south of Tel Aviv) and 34 kilometers south of Caesarea. The site has been excavated continuously during the last 30 years. Once a modest coastal settlement, it became the urban center of the southern Sharon plain as early as the Persian period through the mid-13th century. The city is noted in several Byzantine-period sources. During that time, Apollonia became *Sozousa*, like other sites named after Apollo Soter.[3] Official documents of the synod of Ephesus, held in 449, indicate that, in the mid-fifth century, *Sozousa*/Apollonia was a city in the Byzantine province of *Palaestina Prima*, and that its Christian community was led by a bishop.[4]

In 2006, two new areas (M and O) were excavated at the site.[5] They are contemporaneous with the furnaces discovered in 1950 in the northern part of the site (Areas A and D of Kahane's excavations) and in 2002 in the southern part of the site (Area N of our excavations; Fig. 1).[6] In Area M, which is located in the southern

1. Oren Tal, Ruth E. Jackson-Tal, and Ian C. Freestone, "New Evidence of the Production of Raw Glass at Late Byzantine Apollonia-Arsuf, Israel," *Journal of Glass Studies*, v. 46, 2004, pp. 51–66.

2. *Ibid*., p. 65. From a historical Palestinian perspective, the sixth and seventh centuries refer to the late Byzantine (up to 638), Sassanid (614–628), and early Islamic (from 638) periods. From a material culture Palestinian perspective, these two centuries demonstrate continuity rather than innovation (but with evidence of the abandonment of some military installations, churches, and monasteries); see Jodi Magness, *The Archaeology of the Early Islamic Settlement in Palestine*, Winona Lake: Eisenbrauns, 2003. For this reason, our 2004 publication termed the period of production "late Byzantine" but expressed caution about attributing the raw glass production at the site to either the late Byzantine or the early Islamic period. The context of our 2006 glass production findings (especially in Area M) indicates that glass production at the site began in the sixth century and may have continued into the early Islamic period.

3. A full historical analysis of Byzantine Apollonia-Arsuf is found in Israel Roll and Oren Tal, *Apollonia-Arsuf: Final Report of the Excavations*, v. 1, *The Persian and Hellenistic Periods (with Appendices on the Chalcolithic and Iron Age II Remains)*, Tel Aviv University, Monograph Series of the Institute of Archaeology, no. 16, Tel Aviv: Emery and Claire Yass Publications in Archaeology, 1999, pp. 8–10. For a review of the site's Byzantine history, see Tal, Jackson-Tal, and Freestone [note 1], pp. 51–54.

4. As was conjectured by Karl B. Stark, *Gaza und die philistäische Küste*, Jena: F. Mauke, 1852, p. 452, n. 5; and Charles Clermont-Ganneau, *Archaeological Researches in Palestine during the Years 1873–1874*, v. 2, London: Committee of the Palestine Exploration Fund, 1896, pp. 337–339.

5. The 2006 (18th) season of excavations at the site was carried out by the Institute of Archaeology of Tel Aviv University in collaboration with Brown University and directed by Israel Roll and Oren Tal (TAU) and Katharine Galor (Brown). We were assisted by Moshe Fischer, Ilan Shachar, Tamar Harpak, and Hagi Yohanan, with students from both universities and Israeli and foreign volunteers.

6. Figure 1 is an updated version of the site plan published in Tal, Jackson-Tal, and Freestone [note 1], p. 53, fig. 2. Kahane's Area D, which was recently demolished, is beyond the northern limits of Figure 1.

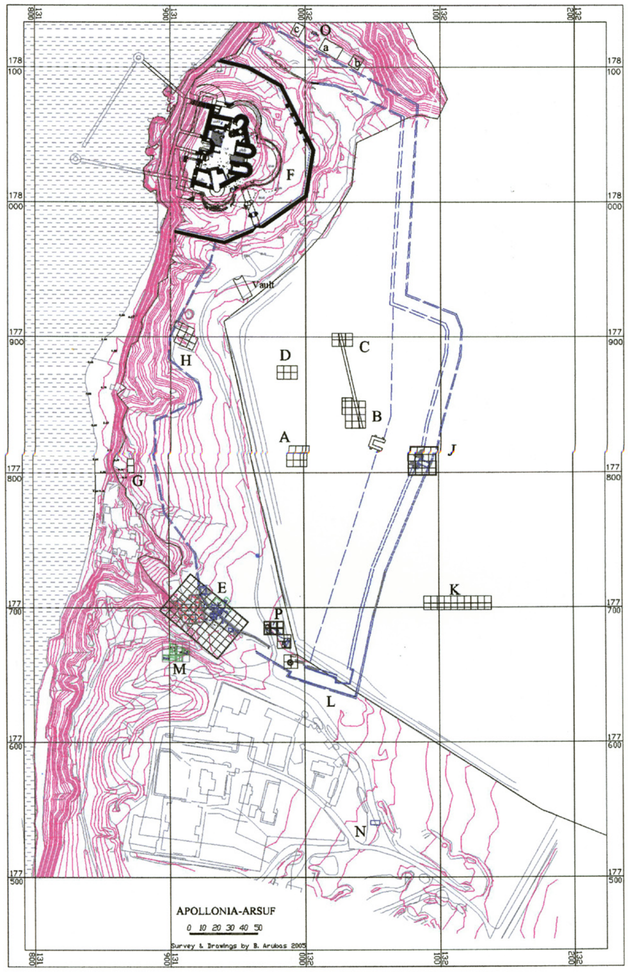

FIG. 1. *Site plan of Apollonia-Arsuf. (Survey and drawing: Benny Arubas)*

part of the site, we excavated a section of the city dump dating to as late as the sixth and seventh centuries. This effort produced some 15 tons of pottery, as well as considerable numbers of raw blue glass chunks (Fig. 2) and fragmentary glass vessels such as bowls, bottles, wineglasses, cosmetic tubes, and lamp bowls dating to the late Byzantine period (Figs. 3 and 4). The glass chunks may suggest refuse from a glass workshop, but no direct evidence of a furnace has been found, and no moils or deformed vessel fragments were recovered, aside from lumps of melted glass that differ from what was found in the furnaces.[7] The late Byzantine dating for the refuse is supported by the thousands of locally made and imported pottery vessels found. These include table vessels (with examples of all of the imported "Late Roman Fine Wares" bowls),[8] cooking vessels, storage vessels (with imported amphorae), and lamps.

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7. Tal, Jackson-Tal, and Freestone [note 1], p. 61, n. 37.

8. For terminology and origin, see John W. Hayes, "Late Roman Fine Wares and Their Successors: A Mediterranean Byzantine Perspective (with Reference to the Syro-Jordanian Situation)," in *La Céramique byzantine et proto-islamique en Syrie-Jordanie (IV^{e}–VIII^{e} siècles apr. J.-C.)*, ed. Estelle Villeneuve and Pamela M. Watson, Bibliothèque Archéologique et Historique, no. 159, Beirut: Institut Français d'Archéologie du Proche-Orient, 2001, pp. 277–278.

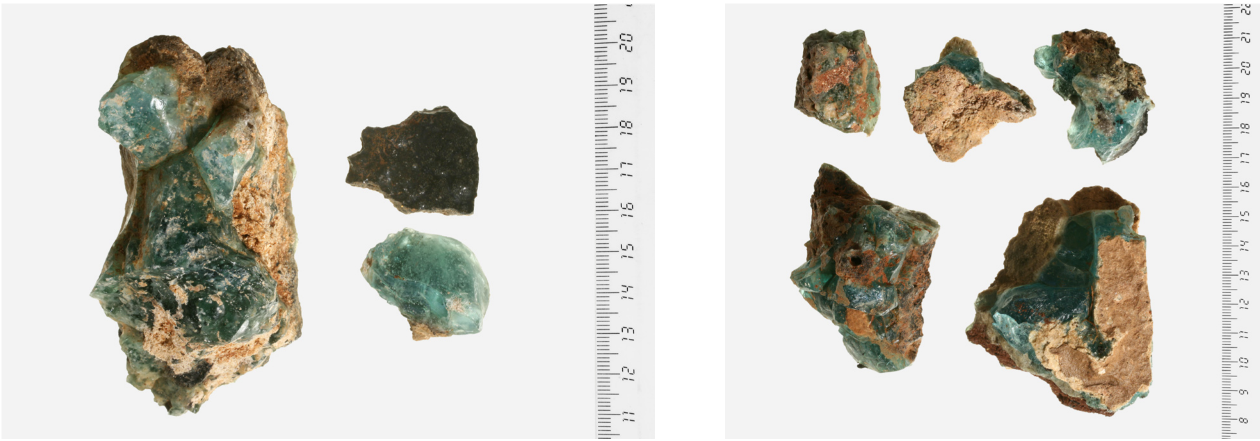

FIG. 2. *Glass chunks from Area M dump* (right) *and Area O furnace* (left). *(Photos: Pavel Shrago)*

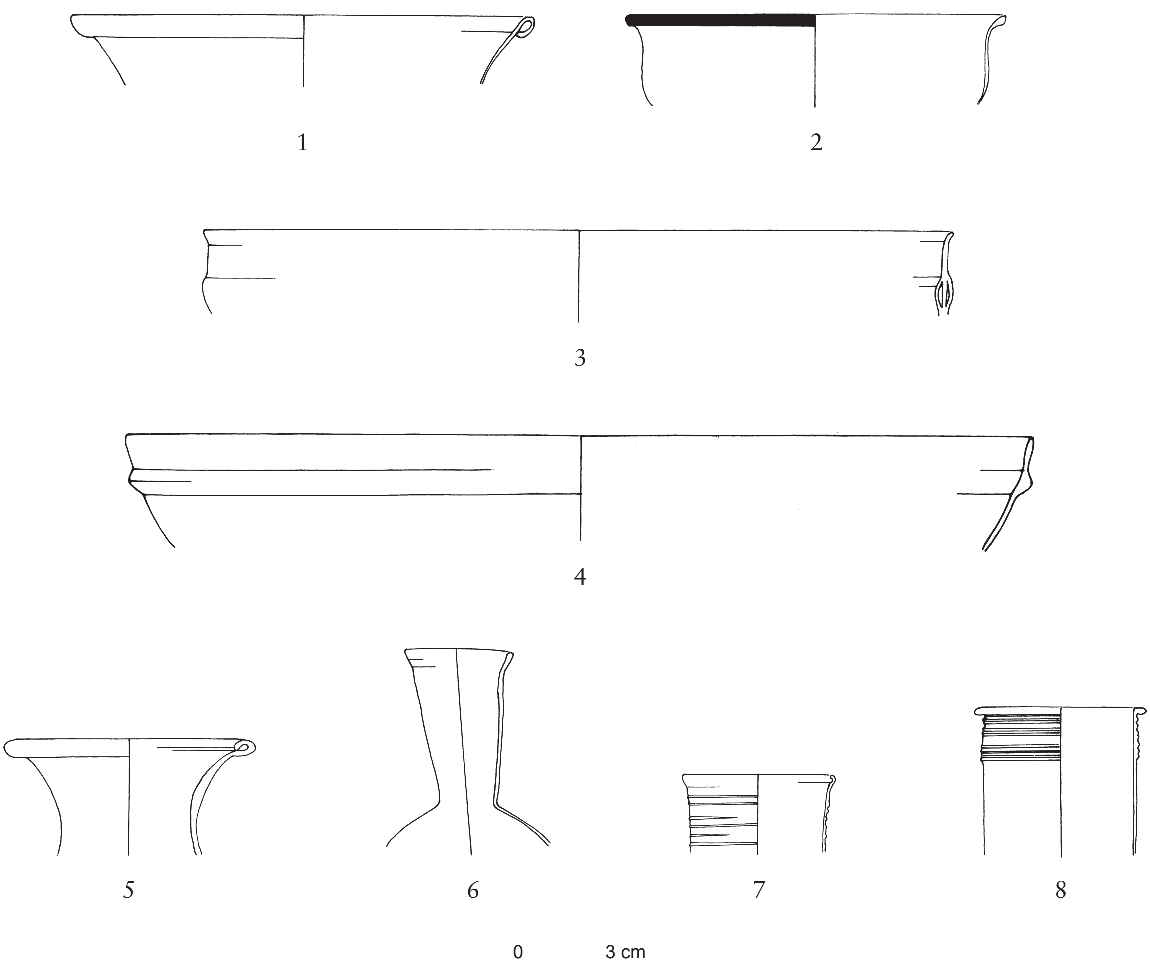

FIG. 3. *Glass bowls and bottles from Area M dump. (Drawings: Ada Perry)*

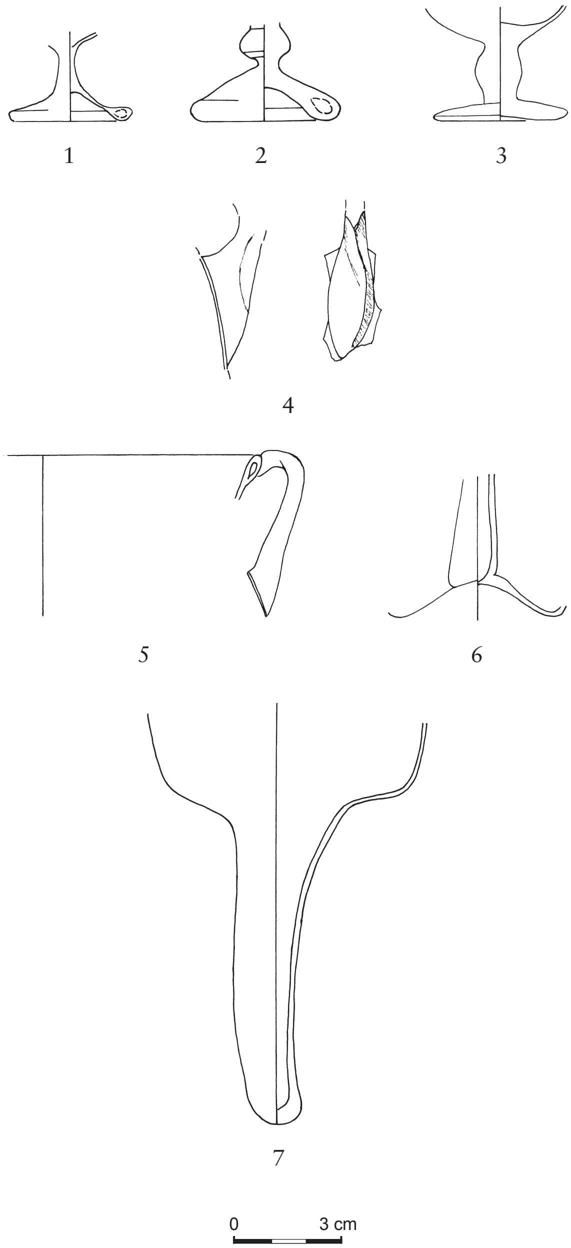

FIG. 4. *Wineglass, cosmetic tube, and lamp bowls from Area M dump. (Drawings: Ada Perry)*

In Area O, a raw glass furnace was discovered. This furnace had probably been dismantled, but remains from its southern section were revealed when we excavated an adjacent mosaic floor from an industrial installation. Chunks of raw blue glass from this floor were extracted for chemical analysis. The attribution of this furnace to the late Byzantine period is conjectural, but because the finds from Area O are not later than the seventh century and because the furnace was constructed in a manner similar to that of the furnace excavated in Area N, it is probable that we have now found a fourth late Byzantine raw glass furnace at Apollonia-Arsuf.

Chemical Analysis

Five raw glass chunks and nine vessel fragments from the Area M dump, and two chunks from the new furnace in Area O, were analyzed by electron microprobe.[9] The results, presented in Table 1,[10] were checked against Corning Mu-

9. Samples were removed from the fragments with clippers and mounted in epoxy resin blocks. Cross sections were ground and then polished using diamond pastes down to 1 μm in diameter. Samples were vacuum-coated with carbon and analyzed using a JEOL JXA-8600 Superprobe at the Institute of Archaeology, University College London, courtesy of Kevin Reeves and Thilo Rehren. Each analysis represents the mean of at least six spots on the glass fragment (typically 2 mm across); average relative standard deviations were 0.4% for SiO_2, 1% for Na_2O, 1% for CaO, 2% for Al_2O_3, 4% for K_2O, 6% for MgO and Fe_2O_3 and Cl, 18% for SO_3, and 33% for P_2O_5.

10. Earlier chemical analyses of Apollonia-Arsuf glass were published by Naomi Porath and Shimon Ilani, “Pigments Derived from Minerals,” in *Colors from Nature: Natural Colors in Ancient Times*, ed. Chagit Sorek and Etan Ayalon, Tel Aviv: Eretz Israel Museum, 1993, p. 10* (and p. 24 in the Hebrew section for the chemical composition of the single chunk sample examined); Robert H. Brill, *Chemical Analyses of Early Glasses*, v. 1, *Catalogue of Samples*, p. 60, and v. 2, *Tables of Analyses*, p. 87, no. 3682, Corning: The Corning Museum of Glass, 1999; Ian C. Freestone, Yael Gorin-Rosen, and Michael J. Hughes, “Primary Glass from Israel and the Production of Glass in Late Antiquity and the Early Islamic Period,” in *La Route du verre: Ateliers primaires et secondaires du second millénaire av. J.-C. au Moyen Age*, ed. Marie-Dominique Nenna, Travaux de la Maison de l’Orient Méditerranéen, no. 33, Lyons: Maison de l’Orient Méditerranéen–Jean Pouilloux, 2001, pp. 69–72, table 2 (four chunks and five vessel samples from Area E, early 1990s excavations); and Tal, Jackson-Tal, and Freestone [note 1], pp. 61–66, table 1 (15 chunk samples). In his 1951 publication, Kahane reported on chemical analysis of chunks discovered in his 1950 excavations that was conducted in the laboratories of the Fenicia glass factory. This analysis showed a composition somewhat similar to that of modern Israeli glass manufactured at the factory. See P. Kahane, “Rishpon (Apollonia), B,” *Bulletin of the Department of Antiquities of the State of Israel*, v. 3, 1951, p. 43 (in Hebrew); an English summary of this report is found in Ann Perkins, “Archaeological News: The Near East,” *American Journal of Archaeology*, v. 55, 1951, pp. 86–87, fig. 11. The chemical composition was never published, however.

seum ancient glass standards A and B,[11] as well as a commercially available glass standard. Small corrections were made to the CaO, Al_2O_3, and Fe_2O_3 values to bring them in line with the standards. To compare the data with previous analyses, compositions were normalized to 100%. Previous results were compared again with the standards analyzed at that time, and a small additional correction (0.1% absolute) was made to the Fe_2O_3 contents.[12] Sample 10 from the Area N furnace has been omitted because it was clearly contaminated by the furnace lining.[13] The average compositions are presented in Table 2.

The glasses from the Apollonia-Arsuf furnaces are soda-lime-silica glasses typical of late Byzantine and early Islamic glass from the Levant. They are characterized by Al_2O_3 contents of about 3%, which are higher than those of most Roman blue-green glass. The soda content is about 15% in the vessel fragments, but slightly lower, on average, in the chunks. Lime is typically in the range of 8%–9%, and silica is typically about 70% (Table 1).

The production technology for this type of composition has been discussed in some detail elsewhere.[14] Certain Palestinian coastal beach sands contain approximately the right concentrations of quartz and calcite so that they could be mixed with soda (probably from the lakes of the Wadi Natrun in Egypt) to produce a blue-green soda-lime-silica glass. This procedure was carried out in large primary tank furnaces of the type excavated at Beth She‘arim, at Beth Eli‘ezer, and in Area N of Apollonia-Arsuf in batches of five to 10 tons. The absence of glassworking debris (moils and distorted vessel fragments) from contexts containing furnaces for the making of raw glass argues in favor of dividing the primary glassmaking and secondary glassworking crafts; these appear to have been located in separate workshops, and they were probably carried out by different craftsmen.[15]

The analyzed glasses from all contexts in Apollonia-Arsuf are similar (Table 2). The most substantive differences are found in silica and soda: SiO_2 is slightly higher and Na_2O is lower in the raw chunks and furnace glasses from Areas M, N, and O, in relation to the Area M vessels and the chunks and vessels from Area E (early 1990s excavations).

Figure 5 compares samples of raw glass chunks from the 2006 and earlier excavations at Apollonia-Arsuf in terms of lime and alumina. These components reflect the mineralogy of the glassmaking sand, with lime representing the calcium carbonate shell fragments and alumina representing the feldspar minerals. Raw glass made in the same area might be expected to be similar in these components. The composition of the chunk glass from the Area M dump overlaps that of raw glass from all other areas of Apollonia-Arsuf, as shown in the central part of the graph, which is consistent with the view that it was made in or around the site.

The two samples of raw glass from the floor of the newly discovered furnace in Area O differ from the other glasses in that their MgO contents are high (> 1%), with slightly high Fe_2O_3 (Tables 1 and 2). Elevated concentrations of iron oxide in chunk glass because of contamination by the furnace wall or crucible are known from Beth Eli‘ezer[16] and the tank in Area N at Apollonia-Arsuf.[17] A large chunk of glass from the Area N furnace had elevated MgO, but this was not reflected in other glass from the tank.[18] In

11. Brill [note 10], v. 2, p. 544.
12. Tal, Jackson-Tal, and Freestone [note 1], pp. 61–65.
13. *Ibid*., pp. 61–62.
14. Robert H. Brill, "Scientific Investigations," in Gladys Davidson Weinberg, *Excavations at Jalame: Site of a Glass Factory in Late Roman Palestine*, Columbia: University of Missouri Press, 1988, pp. 257–294; Ian C. Freestone and Yael Gorin-Rosen, "The Great Glass Slab at Beth She‘arim, Israel: An Early Islamic Glassmaking Experiment?" *Journal of Glass Studies*, v. 41, 1999, pp. 105–116; I. C. Freestone and others, "Strontium Isotopes in the Investigation of Early Glass Production: Byzantine and Early Islamic Glass from the Near East," *Archaeometry*, v. 45, no. 1, February 2003, pp. 19–32.
15. E.g., I. C. Freestone, M. Ponting, and M. J. Hughes, "The Origins of Byzantine Glass from Maroni Petrera, Cyprus," *Archaeometry*, v. 44, no. 2, May 2002, pp. 257–272, esp. figs. 1 and 2.
16. Freestone, Gorin-Rosen, and Hughes [note 10], p. 77, analysis 40.
17. Tal, Jackson-Tal, and Freestone [note 1], table 1, analysis 10.
18. *Ibid*., table 1, analyses 1–3.

TABLE 1

Compositions of Glasses from 2006 Excavations at Apollonia-Arsuf
(Electron Microprobe Analysis)

	M *7034* *70787* *Lump* *1*	*M* *7010* *70168* *Lump* *2*	*M* *7005* *70361* *Lump* *3*	*M* *7008* *70047* *Lump* *4*	*M* *7029* *70094* *Lump* *5*	*O* *8001* *80001* *Mosaic Lump* *6*	*O* *8002* *80002* *Mosaic Lump* *7*	*M* *7008* *70096* *Vessel* *8*
SiO_2	72.55	70.76	72.22	70.70	69.53	70.25	69.03	70.82
TiO_2	0.11	0.10	0.06	0.10	0.11	0.13	0.13	0.09
Al_2O_3	3.15	3.32	3.05	3.37	3.13	3.09	3.06	3.10
Fe_2O_3	0.64	0.65	0.40	0.64	0.50	0.74	0.79	0.58
MnO	0.02	0.02	0.02	0.03	0.01	0.02	0.01	0.04
MgO	0.64	0.67	0.43	0.67	0.53	1.14	1.82	0.64
CaO	8.48	9.80	7.14	9.70	8.70	8.45	9.71	8.42
Na_2O	12.78	13.12	15.10	13.23	15.03	14.57	13.81	14.49
K_2O	0.76	0.67	0.57	0.68	1.26	0.67	0.72	0.85
P_2O_5	0.10	0.06	0.04	0.07	0.13	0.04	0.05	0.09
SO_3	0.04	0.11	0.14	0.11	0.11	0.11	0.11	0.14
Cl	0.74	0.72	0.85	0.71	0.95	0.79	0.76	0.74
Totals	101.11	101.20	100.85	100.99	101.08	100.81	101.04	101.07

Data normalized to 100%. Original totals given.

TABLE 2

Mean Compositions of All Analyses of Glass from Apollonia-Arsuf

	Area E Chunk		*Area E Vessel*		*Area N Furnace*	
	m (4)	*sd*	*m (5)*	*sd*	*m (14)*	*sd*
SiO_2	69.88	*1.80*	71.38	*1.83*	71.97	*1.55*
Al_2O_3	3.12	*0.22*	3.01	*0.08*	3.38	*0.14*
Fe_2O_3	0.55	*0.17*	0.41	*0.04*	0.46	*0.05*
MgO	0.70	*0.02*	0.58	*0.09*	0.63	*0.20*
CaO	8.74	*1.35*	7.56	*1.54*	8.29	*0.86*
Na_2O	15.04	*0.53*	15.30	*1.11*	13.65	*1.12*
K_2O	0.85	*0.46*	0.61	*0.14*	0.52	*0.14*
P_2O_5	<0.10		<0.10		0.05	*0.01*
Cl	0.79	*0.09*	0.88	*0.09*	0.84	*0.08*
SO_3	0.33	*0.07*	0.28	*0.11*	0.10	*0.05*

m (4) = mean of four analyzed samples. sd = standard deviation (in italics).

M	*M*	*M*	*M*	*M*	*M*	*M*	*M*
7008	*7008*	*7010*	*7010*	*7010*	*7012*	*7012*	*7012*
70096	*70096*	*70209*	*70209*	*70209*	*70378*	*70378*	*70378*
Vessel	*Vessel*	*Vessel*	*Vessel*	*Vessel*	*Vessel*	*Vessel*	*Vessel*
9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
70.82	69.83	70.14	70.26	70.16	71.09	70.72	70.43
0.09	0.10	0.11	0.09	0.11	0.06	0.07	0.09
3.08	3.23	3.15	2.91	3.09	3.17	3.02	3.09
0.51	0.58	0.62	0.51	0.62	0.38	0.44	0.52
0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.54	0.54	0.84	0.67	0.88	0.52	0.58	0.65
7.80	8.64	8.77	7.74	8.51	8.10	8.57	8.31
15.55	15.23	14.56	16.33	14.93	15.15	15.00	15.25
0.52	0.86	0.80	0.58	0.72	0.45	0.54	0.64
0.04	0.09	0.07	0.05	0.06	0.03	0.09	0.06
0.11	0.15	0.12	0.24	0.14	0.14	0.05	0.13
0.93	0.72	0.80	0.61	0.76	0.88	0.88	0.80
100.88	100.84	100.96	100.03	100.80	100.51	100.66	100.67

Area M Chunk		*Area M Vessel*		*Area O Furnace*	
m (5)	*sd*	*m (9)*	*sd*	*m (2)*	*sd*
71.15	*1.23*	70.48	*0.39*	69.64	*0.87*
3.20	*0.14*	3.10	*0.09*	3.08	*0.02*
0.57	*0.11*	0.53	*0.08*	0.77	*0.04*
0.59	*0.11*	0.65	*0.12*	1.48	*0.48*
8.76	*1.08*	8.32	*0.34*	9.08	*0.89*
13.85	*1.12*	15.16	*0.52*	14.19	*0.54*
0.79	*0.27*	0.66	*0.14*	0.70	*0.04*
0.08	*0.03*	0.07	*0.02*	0.04	*0.00*
0.79	*0.11*	0.79	*0.09*	0.77	*0.02*
0.10	*0.03*	0.14	*0.05*	0.11	*0.00*

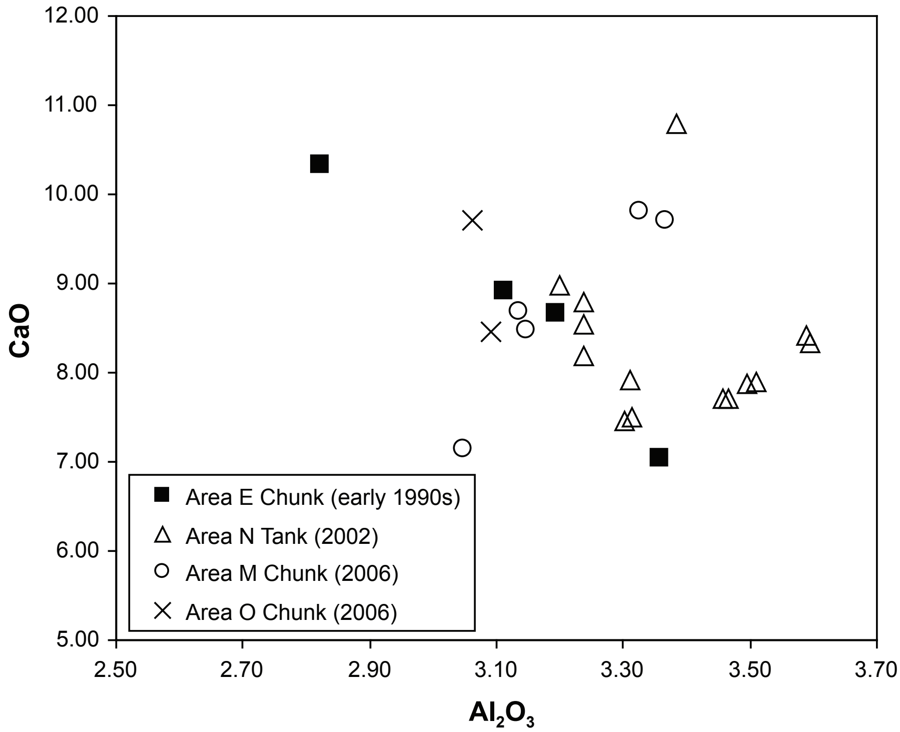

FIG. 5. *Lime and alumina contents of raw (chunk) glass from Apollonia-Arsuf.*

an assemblage of sixth- and seventh-century Levantine glass from the church at Maroni Petrera, Cyprus, two samples had notably higher MgO.[19] The Area O samples do not have higher Al_2O_3, which would also be expected if the glass was contaminated by ceramic. Even so, it seems unlikely that these high iron and magnesium oxide contents are representative of the entire output of the furnace. These samples were removed from the furnace floor and presumably indicate some localized contamination by soil or ash, or a local variation in the composition of the glassmaking sand.

The vessel glass from Area M is compared with the raw glass from all areas of Apollonia-Arsuf in Figure 6. Also shown are the compositions of the Byzantine workshop assemblages (chunks, vessels, and waste) from Beth Shean[20] and Ramla (South).[21] The Area M vessels and the workshop assemblages from Beth Shean and Ramla (South) have limited compositional ranges in relation to the raw glass, and the fields that they define are about the same size and significantly smaller than the field defined by the raw glass. This indicates that the analyzed Area M glass vessels show the same compositional variation as glass produced by a secondary workshop, and suggests that these vessels were the products of a single workshop. Thus, while the Area M debris may not be a workshop assemblage, in that it contains no workshop waste, the recovered vessels appear to be products of a secondary workshop in Apollonia-Arsuf.

19. Freestone, Ponting, and Hughes [note 15], table 1.

20. Ian C. Freestone and Yael Gorin-Rosen, unpublished data. For the archeological evidence, see Yael Gorin-Rosen, "The Ancient Glass Industry in Israel: Summary of the Finds and New Discoveries," in *La Route du verre* [note 10], pp. 59–60.

21. Oren Tal, Ruth E. Jackson-Tal, and Ian C. Freestone, "Glass from a Late Byzantine Secondary Workshop at Ramla (South), Israel," pp. 81–95 in this volume.

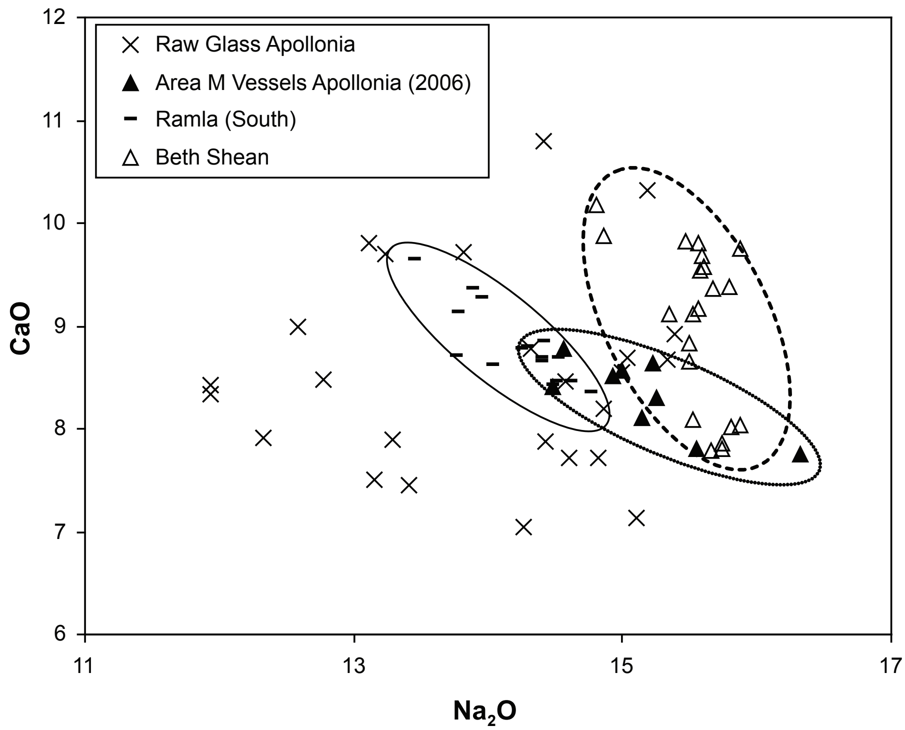

FIG. 6. *Glass vessels from Apollonia-Arsuf (Area M) compared with vessels and chunk glass from workshops at Beth Shean and Ramla (South), as well as all raw glass from Apollonia-Arsuf furnaces.*

The relationship between the main components—soda, lime, silica, and alumina—in the vessels and chunk glass from Area M is shown in Figure 7. These graphs demonstrate that the compositions of the vessel glasses and the chunks are not identical. The former fall mainly within the compositional range of the latter, but they are more tightly clustered. This would be expected if the chunks were samples of the raw material from which the vessels were made. As has been discussed elsewhere,[22] workshop products have a more limited compositional range than the raw materials from which they were fashioned because the raw glass and cullet are mixed together in the workshop furnace in order to create a more homogeneous composition. This appears to be shown by the Area M assemblage. These chunk glasses may well have been part of the raw material employed by the workshop in fashioning the vessels.

The tank furnaces at Beth Eli'ezer, Hadera, are believed to have been in operation during the eighth century because the glass they produced matches that of Umayyad vessels from Ramla.[23]

22. Jennifer Price, Ian C. Freestone, and Caroline R. Cartwright, "'All in a Day's Work'? The Colourless Cylindrical Glass Cups Found at Stonea Revisited," in *Image, Craft and the Classical World: Essays in Honour of Donald Bailey and Catherine Johns*, ed. Nina Crummy, Monographies Instrumentum, no. 29, Montagnac: Editions Monique Mergoil, 2005, pp. 163–169; Ian C. Freestone, Jennifer Price, and Caroline R. Cartwright, "The Batch: Its Recognition and Significance," *Annales de l'Association Internationale pour l'Histoire du Verre*, v. 17, Antwerp, 2006, in press.

23. Freestone, Gorin-Rosen, and Hughes [note 10], p. 72; Ian C. Freestone, Richard Greenwood, and Yael Gorin-Rosen, "Byzantine and Early Islamic Glassmaking in the Eastern Mediterranean: Production and Distribution of Primary Glass," in *Hyalos-Vitrum-Glass: History, Technology, and Conservation of Glass and Vitreous Materials in the Hellenic World*, ed. George Kordas, Athens: Glasnet Publications, 2002, p. 170.

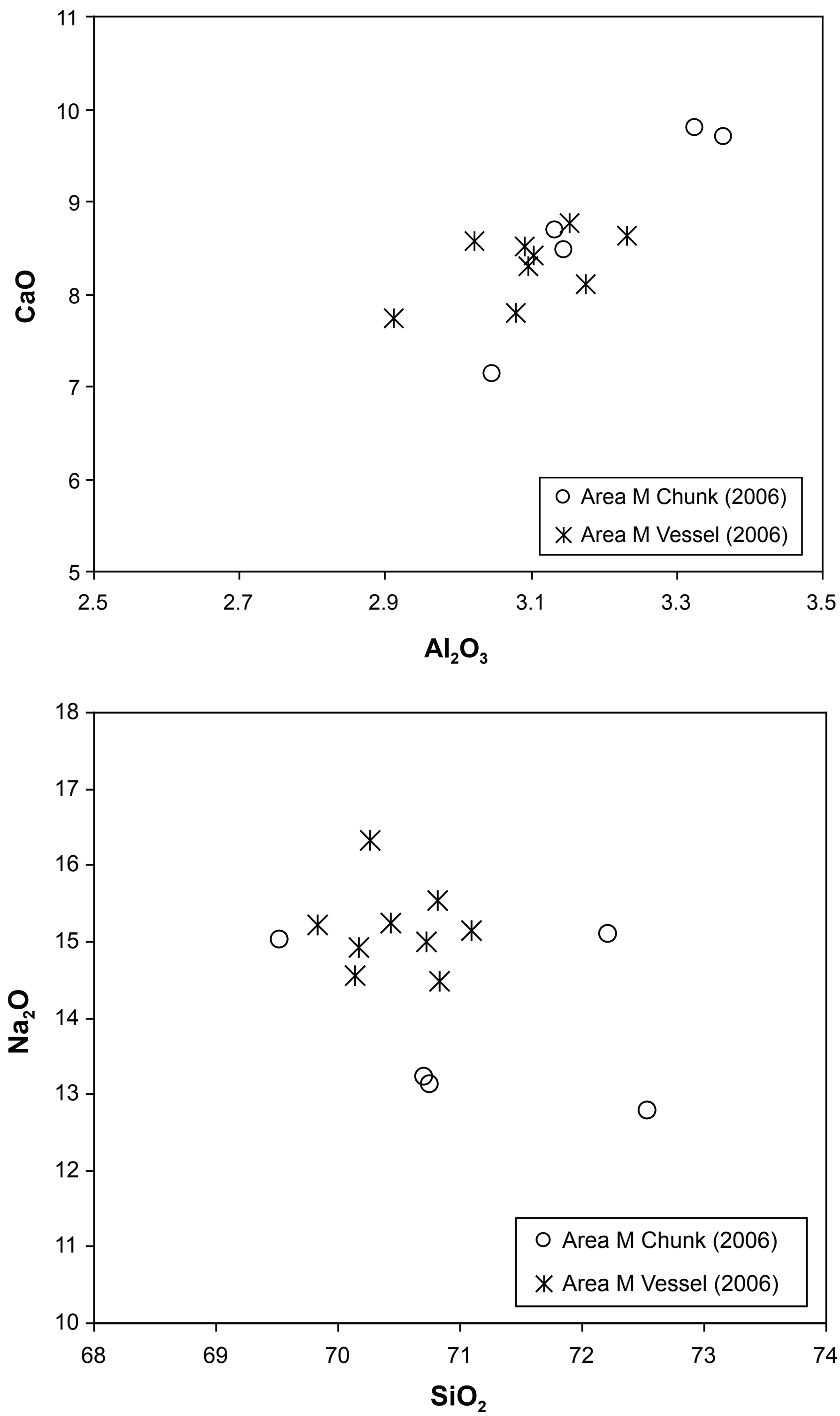

FIG. 7. *Relationship between compositions of raw chunks and vessel glass from Area M at Apollonia-Arsuf in terms of lime and alumina* (top) *and soda and silica.*

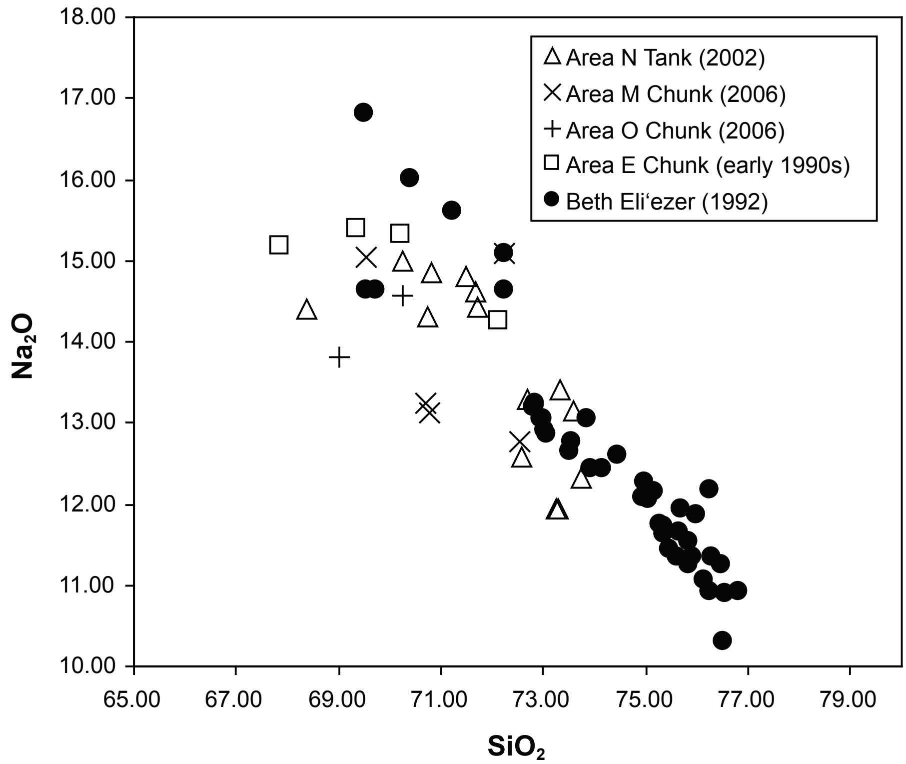

FIG. 8. *Soda and silica contents of raw glass from Apollonia-Arsuf and Beth Eli'ezer.*

Figure 8 compares glass from these furnaces[24] with raw glass from Apollonia-Arsuf in terms of soda and silica. Although there is some overlap, these glasses differ in several respects. Apollonia-Arsuf glass tends to be higher in soda and lime and lower in silica, which is reflected by the displacement of the Apollonia-Arsuf analyses toward the origin in the diagram. The sands used at Apollonia-Arsuf seem to have contained more lime than those at Beth Eli'ezer, while the lower soda content in the early Islamic glass reflects a chronological trend of declining soda in glass produced in the region, which has been noted elsewhere.[25] The analyzed Apollonia-Arsuf chunk glasses, which came from as many as four tank furnaces, are broadly similar to samples from Beth Eli'ezer, suggesting a related output at the two locations but a difference in the composition of the glasses. The similarity in production might be expected of groups of furnaces operating in the same region. In earlier work, based on a significantly smaller sample, glass from Apollonia-Arsuf was grouped with glass labeled "Levantine I," while glass from Beth Eli'ezer was termed "Levantine II."[26] Such a distinction still appears reasonable, although there is a greater compositional overlap than was previously evident. However, the chronological relationship between these groups appears to be more com-

24. Freestone, Gorin-Rosen, and Hughes [note 10], pp. 77–78, table 2.

25. Alysia Fischer and W. Patrick McCray, "Glass Production Activities as Practised at Sepphoris, Israel (37 BC–AD 1516)," *Journal of Archaeological Science*, no. 26, 1999, pp. 893–905; Freestone, Gorin-Rosen, and Hughes [note 10], p. 74; Julian Henderson, "Tradition and Experiment in First Millennium A.D. Glass Production: The Emergence of Early Islamic Glass Technology in Late Antiquity," *Accounts of Chemical Research*, v. 35, 2002, pp. 594–602.

26. Freestone, Gorin-Rosen, and Hughes [note 10].

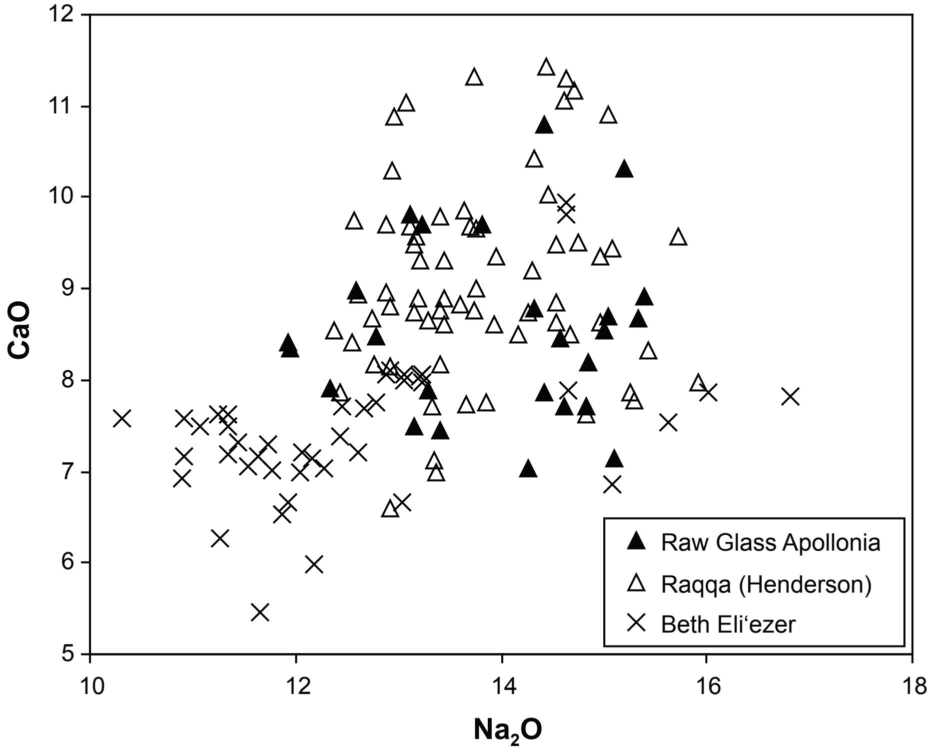

FIG. 9. *Levantine glass from Raqqa (data of Henderson and others [note 27]) compared with raw glass from Apollonia-Arsuf and Beth Eli'ezer.*

plex than was earlier believed. Glass with characteristics similar to Levantine I has been recovered from early Islamic contexts at Raqqa, Syria, which originated on the Levantine coast, according to isotopic analysis.[27] Figure 9 compares raw glass from Apollonia-Arsuf and Beth Eli'ezer with all natron-type glass from Raqqa in terms of soda and lime.[28] The close compositional relationship between late Byzantine glass from Apollonia-Arsuf and early Islamic glass from Raqqa is clear, while the Beth Eli'ezer glass typically has lower lime than either of these groups. Hence, glass corresponding to the Levantine I type was being used, and presumably was also made, in the early Islamic and late Byzantine periods.

The very large compositional spread of the glass from Raqqa (Fig. 9) in relation to the vessel assemblage from Area M at Apollonia-Arsuf and the workshop assemblages from Beth Shean and Ramla (Fig. 6) probably reflects the scale and date of glassworking at Raqqa, which employed many different consignments of raw glass and/or cullet (broken vessels). Large compositional spreads are also seen in consumption assemblages such as those from the churches of Maroni Petrera, Cyprus,[29] and Petra, Jordan,[30] where

27. J. Henderson, S. D. McLoughlin, and D. S. McPhail, "Radical Changes in Islamic Glass Technology: Evidence for Conservatism and Experimentation with New Glass Recipes from Early and Middle Islamic Raqqa, Syria," *Archaeometry*, v. 46, no. 3, August 2004, pp. 439–468. For isotopes and the origin of the Raqqa glass, see J. Henderson and others, "The Use of Oxygen, Strontium and Lead Isotopes to Provenance Ancient Glasses in the Middle East," *Journal of Archaeological Science*, v. 32, no. 5, May 2005, pp. 665–673.

28. Data of Henderson, McLoughlin, and McPhail [note 27], table 1. For our purposes, the cutoff composition for "natron glass" was taken at 1.3% K_2O.

29. Freestone, Ponting, and Hughes [note 15].

30. N. Schibille, F. Marii, and T. Rehren, "Characterization and Provenance of Late Antique Window Glass from the Petra Church in Jordan," *Archaeometry*, v. 50, in press.

it might also be expected that the sampled glasses represent production over a long period.

Conclusions

The furnaces discovered in Apollonia-Arsuf are the only primary glass installations in Palestine that have so far been confirmed as operating in the late Byzantine period. They are also the earliest identified primary glassmaking furnaces in that region.

The discovery of additional evidence of primary glass production in Apollonia-Arsuf has yielded interesting preliminary results on a number of key issues. The tanks produced glass of similar composition, working with the same recipes and the same raw materials. Glass vessels from a dump in Area M show a relatively tight compositional cluster, suggesting that they were produced in a single workshop. Glasses from secondary workshops of that period at Beth Shean and Ramla (South) are also tightly clustered, while Levantine glass from Raqqa displays a wide spread, probably reflecting the scale and longevity of the glassworking operation there.

The new discoveries at Apollonia-Arsuf and their chemical analysis strongly suggest that raw glass produced at the site was also used to make the glass vessels that have been found there. This does not necessarily mean that vessel glass was manufactured there. We have no clear archeological evidence such as vessel-producing furnaces and debris from secondary glass production. However, given the size of the city and the fact that it produced primary glass, the presence of secondary glass production there is very probable, and it seems very likely that both industries coexisted in the city, although they were practiced by different craftsmen.[31]

If, as we have suggested, Apollonia-Arsuf crafted vessels from raw glass produced there, the site must be considered as a major center for the manufacture of both primary and secondary glass in the sixth and seventh centuries. Although it is possible that other sites made primary and secondary glass in late Byzantine Palestine, large-scale primary production is likely to have been limited to only a few locations where suitable coastal sand deposits could be obtained. Furthermore, the requisite knowledge of primary glass production would have been held by only a limited number of artisans who may have been related by clan or family ties. Such specialized knowledge is suggested in particular by such common features as the aspect ratios of tank furnaces at Beth She‘arim, Beth Eli‘ezer, Apollonia-Arsuf, and Tyre.[32] To date, only Apollonia-Arsuf has yielded evidence for the coexistence of primary and secondary industries, and even here the evidence is indirect, so we cannot be certain just how closely related these workshops were in that city. The only other documented evidence of full production in the region—from raw glass to the blowing of vessels—has been provided by Julian Henderson for Tell Fukhkhar in Raqqa, Syria, but at a much later date (the 11th and 12th centuries).[33] Henderson and his colleagues have also noted that primary and secondary

31. The distinction between the primary production of raw glass and the secondary production of glass vessels is well attested in historical, archeological, and ethnographic studies. See, for example, Freestone, Gorin-Rosen, and Hughes [note 10], p. 66; and Gorin-Rosen [note 20], p. 50. This distinction was based on the different needs for each activity (e.g., the proximity to raw materials for the glass composition and firing process, and adequate winds for the production of raw glass). Therefore, at a given site, the production of raw glass was located away from the residential area, while secondary production was found in the very heart of the community.

32. Tal, Jackson-Tal, and Freestone [note 1], p. 60. The length:width ratio of the melting chambers is approximately 1.5:1.

33. Julian Henderson, “Glass Trade and Chemical Analysis: A Possible Model for Islamic Glass Production,” in *Echanges et commerce du verre dans le monde antique: Actes du colloque de l’Association Française pour l’Archéologie du Verre, Aix-en-Provence et Marseille, 7–9 juin 2001*, ed. Danièle Foy and Marie-Dominique Nenna, Montagnac: Editions Monique Mergoil, 2003, pp. 109–111. The coexistence of primary and secondary industries was recently claimed for another Palestinian site of the Byzantine and early Islamic periods. See Yael Gorin-Rosen, “The Glass Finds from Ḥorbat Hermas,” *‘Atiqot*, v. 51, 2006, pp. 34*–35* (in Hebrew; English summary, p. 236), but here the evidence for primary glass production is scant and unclear.

glass may have been produced together at another site, Tell Zujaj, Raqqa, in the late eighth and ninth centuries, but again this evidence is indirect: the secondary circular furnaces are sealed by debris from tank furnaces that is reasonably construed to be of about the same date.[34] Furnace morphology does not necessarily distinguish primary and secondary production. It appears that much of the secondary glass produced in ancient times was melted in tanks rather than in crucibles.

The case study presented in this article is part of an increasing interdisciplinary trend of utilizing chemical analysis to draw archeological conclusions about the past. While the analysis of raw glass from furnaces yields useful information about composition, dating, and provenance, it is becoming increasingly clear that to fully understand issues of dating, workshop activity, and technological and consumer choice, the analysis of carefully characterized forms from secondary workshops and nonindustrial contexts is required. It appears that the Byzantine glassmaking industry of the Levant and Egypt supplied glass to much of the world in late antiquity—from Cyprus[35] to Italy[36] and, eventually, northwestern Europe.[37] An understanding of glassmaking and glassworking in the region, as well as the compositional relationship between finished products and raw materials, is necessary if we are to make sense of the operation of the glass industry elsewhere and to accurately interpret consumer assemblages of glass.

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34. Henderson, McLoughlin, and McPhail [note 27], pp. 441–442.

35. Freestone, Ponting, and Hughes [note 15], pp. 257–272.

36. Freestone, Greenwood, and Gorin-Rosen [note 23], pp. 167–174.

37. Ian C. Freestone, "Primary Glass Sources in the Mid First Millennium AD," *Annales de l'Association Internationale pour l'Histoire du Verre*, New York and Corning, 2001 (Nottingham, 2003), pp. 111–115.