Journal of Glass Studies **42**, 2000, 13-24

NEW ASPECTS OF ANCIENT EGYPTIAN GLASSMAKING

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DESPITE MUCH RESEARCH in early glass technology, relatively little is known about the way(s) in which glass was made in the Late Bronze Age (LBA), particularly in Egypt. In an attempt to add fresh lines of argument to the debate, this article considers what the base glass composition of LBA glasses can tell us about the technology used in their manufacture.[1] Of course, any suggestions deriving from this theoretical approach have to be tested against the archeological record, faint as it is. In the absence of direct evidence for Egyptian glassmaking installations, LBA glass ingots and related crucible fragments and technical debris were studied.

About the only thing we can safely assume about the making of LBA Egyptian raw glass is the use of a plant ash-type soda[2] and some form of quartz as the main batch ingredients. We do not know, however, whether a fritting step preceded the actual glass melting,[3] nor can we say anything for certain about the furnaces or installations used. It is tempting to suggest that two circular furnace pits recently unearthed in Tell el-Amarna were glassmaking furnaces,[4] but all we know for sure is that they clearly differ from known LBA pottery kilns and metallurgical furnaces. Only when it comes to the production of colored glass ingots are we on relatively sound archeological ground, in the form of abundant crucible remains from various New Kingdom (NK) sites in Egypt[5] and some ingots. These glass ingots, which evidently were articles of trade (about 175 examples were exca-

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[1] This study was undertaken as part of the 1998 Rakow Grant for Glass Research, which is gratefully acknowledged here. Particular thanks go to P. Rogers and the staff of the Juliette K. and Leonard S. Rakow Research Library of The Corning Museum of Glass for all their patience and the help they extended to me, and to Dr. R. Brill for many instructive and fruitful discussions.

[2] I. Freestone, "Composition and Microstructure of Early Opaque Red Glasses," in *Early Vitreous Material*, ed. M. Bimson and I. Freestone, British Museum Occasional Papers, v. 17, London, 1987, pp. 173–191; C. Lilyquist and others, "Part 2. Glass," in *Studies in Early Egyptian Glass*, ed. C. Lilyquist and R. Brill, New York: The Metropolitan Museum of Art, 1993, pp. 23–58.

[3] The cuneiform glassmaking texts, which are probably post-LBA, suggest that fritting was used in Mesopotamia. See R. H. Brill, "Some Chemical Observations on the Cuneiform Glassmaking Texts," *Annales du 5e Congrès de l'Association Internationale pour l'Histoire du Verre*, Liège: Musée du Verre, 1972, p. 332.

[4] C. Jackson, P. Nicholson, and W. Gneisinger, "Glassmaking at Tell el-Amarna: An Integrated Approach," *Journal of Glass Studies*, v. 40, 1998, pp. 11–23.

[5] W. E. S. Turner, "Studies in Ancient Glasses and Glassmaking Processes. Part I: Crucibles and Melting Temperatures Employed in Ancient Egypt at About 1370 B.C.," *Journal of the Society of Glass Technology*, v. 38, 1954, pp. 436T–444T; Th. Rehren, "Ramesside Glass Colouring Crucibles," *Archaeometry*, v. 39, 1997, pp. 355–368; Th. Rehren and E. Pusch, "New Kingdom Glass Melting Crucibles from Qantir-Piramesses," *Journal of Egyptian Archaeology*, v. 83, 1997, pp. 127–141; P. Nicholson, C. Jackson, and K. Trott, "The Ulu Burun Glass Ingots, Cylindrical Vessels and Egyptian Glass," *Journal of Egyptian Archaeology*, v. 83, 1997, pp. 143–153.

vated from the Uluburun wreck[6]) despite their lack of any decorative or immediately functional value, represent the final step in glassmaking, and thus serve as the interface to any subsequent artistic glassworking (i.e., the production of finished glass objects).

Base Glass Composition as an Indicator of Batch Melting

At first glance, the composition of a given glass reflects its initial batch composition, with some allowance for minor changes due to furnace reactions and the addition of colorants. This concept, hereafter labeled the "total batch melting" model, certainly applies to the making of most medieval and later glasses, with variances in composition often being linked to the specific region or period in which the glasses were made. By contrast, the vast majority of LBA Egyptian glasses analyzed to date show remarkably few changes in chemical composition, regardless of color, type of object, findplace, or date.[7]

This article is based primarily on data provided in a recent publication by Lilyquist and Brill,[8] which offers what is probably the largest collection of information on well-provenanced and -dated early Egyptian glass, covering a wide range of colors, object types, and dates. Also taken from that monograph is the idea of a "base glass composition" (or "reduced composition")—consisting of silica, alumina and iron oxide, soda and potash, and lime and magnesia—to describe the basic glass, to which only colorants and opacifiers were later added. By re-normalizing the constituents of the base glass to 100 weight percent, different glasses can be compared regardless of their color. With colorant-related element concentrations running as high as five to 10 percent for certain colors, this normalization procedure is particularly necessary.

The striking homogeneity in the composition of the base glass indicates, in terms of a "total batch melting" model, that LBA glassmaking throughout the Near and Middle East was either highly centralized, relying on only one or two major glassmaking centers, or that glassmaking recipes were strictly followed all over the region, remaining unchanged for several centuries. In either case, the supply of raw materials must have been stable and reliable, with almost no compositional variation in the plant ash and quartz sources used.

The "Partial Batch Melting" Model

Using a method of data reduction that is described in more technical detail in the Appendix, it was found that most of the LBA glasses studied to date plot onto (or very close to) a particular low-temperature-melting region, commonly called the "eutectic trough," of the relevant phase diagram (Fig. 1).[9] It seems highly unlikely that this grouping is simply accidental, given the consistency with which the glasses adhere to this particular composition, even though there presumably was considerable vari-

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[6] G. Bass, "A Bronze Age Shipwreck at Ulu Burun (Kaş): 1984 Campaign," *American Journal of Archaeology*, v. 90, 1986, pp. 269–296; C. Pulak, "The Uluburun Shipwreck," in *Res Maritimae, Cyprus and the Eastern Mediterranean from Prehistory to Late Antiquity*, ed. S. Swiny, R. Hohlfelder, and H. Swiny, Atlanta, Georgia, 1997, pp. 233–262.

[7] E. Caley and E. Sayre were probably the first to recognize this phenomenon, and all subsequent analyses corroborated it. See E. Caley, "Analyses of Ancient Glasses, 1790–1957," Corning Museum of Glass Monographs, v. 1, Corning, New York: the museum, 1962; and E. Sayre, "Summary of the Brookhaven Program of Analysis of Ancient Glass," in *Application of Science in Examination of Works of Art*, ed. W. Young, 1965, pp. 145–154.

[8] C. Lilyquist and R. Brill, eds., *Studies in Early Egyptian Glass*, New York: The Metropolitan Museum of Art, 1993.

[9] K. Shahid and F. Glasser, "Phase Equilibria in the Glass Forming Region of the System Na_2O-CaO-MgO-SiO_2," *Physics and Chemistry of Glasses*, v. 13, no. 2, 1972, pp. 27–42.

ation in the raw materials from which they were made.

I would argue, instead, that this tight clustering results from a self-adjusting mechanism that controls the composition of a melt forming from any batch, provided that the starting ingredients are present in broadly suitable proportions. However, in order to generate a melt whose composition differs from that of the initial batch, it is necessary to have residual material whose composition balances the difference in composition between the initial batch and the resulting melt. If the entire batch were melted, the glass formed from it would, of course, mirror the batch composition. Unless the melting temperature is sufficiently high to reach total batch melting, or the batch composition matches the eutectic composition, the composition of the initial partial melt will start in the system's lowest melting temperature region. Then, with increasing temperature, it moves upward along the eutectic trough nearest to the bulk batch composition. Along the way, the partial melt will selectively incorporate the compounds from the batch that are necessary to follow the path dictated by the phase diagram and, at the same time, form as much melt phase as possible at any given temperature until one of the crucial ingredients is no longer available. Only then, and with still increasing temperature, can the melt composition leave the eutectic trough without violating fundamental equilibrium conditions. This mechanism, which is well known from magma evolution in igneous petrology, alloy melting in metallurgy, and slag forming in iron smelting, forces the melt to take on a neatly defined composition. This composition is controlled only by the course of the appropriate eutectic trough and the maximum temperature reached in melting.[10]

Implications of the Proposed Model

The first information we can derive from plotting the chemical data into the diagram concerns the melting temperature of the glass. Most of the samples have a theoretical melting temperature of between 900° and 1,000°C, but a few (nos. 16, 31, and 34) were melted at temperatures as low as 800°C. This temperature range is considerably lower than that of a "clean" soda-lime-silica glass of similar composition, and is well within the refractory limits of the crucibles in which the glass was worked.[11] The melting temperatures, which are significantly lower than expected, are due primarily to the substitution of magnesia for lime—which, at the 5 wt % MgO typically encountered in LBA glasses, lowers the melting temperatures by almost 100°C.[12] A similar, though less pronounced, effect is produced by the presence of small amounts of each of the other minor compounds. Thus, the actual melting temperatures of these glasses should be even lower than indicated here.[13]

Other information that can be drawn from this model, and particularly from the link between the tight clustering of NK glass analyses and the specific liquidus shape of that quasi-ternary phase diagram, is less immediate but prob-

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[10] This scenario will be true only under equilibrium conditions. In reality, there are influences from reaction kinetics, diffusion rates, etc., which will result in some deviation from the ideal. For the general purpose of this article, and in view of other simplifications of the data, this may still suffice. For a more technical and general discussion of this model, see Th. Rehren, "Rationales in Old World Base Glass Compositions," *Journal of Archaeological Science*, v. 27, 2000.

[11] Turner [note 5].

[12] Shahid and Glasser [note 9].

[13] Due to slow-reaction kinetics, the adjustment of the melt composition will be considerably delayed, particularly below 1000°C. Thus, the necessary furnace temperatures were certainly higher than those deduced from the melt composition.

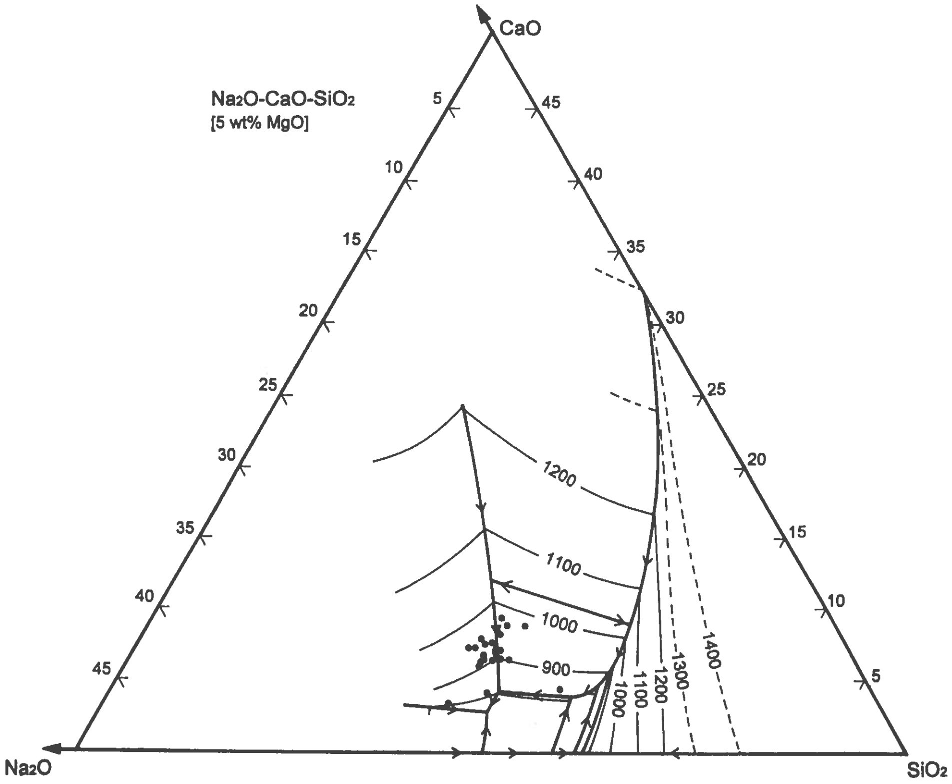

FIG. 1. *Reduced base glass compositions of Egyptian glasses from Amenhotep II and later. (Original data from C. Lilyquist and R. Brill, eds.,* Studies in Early Egyptian Glass, *New York: The Metropolitan Museum of Art, 1993.)*

ably even more important from an archeological standpoint.

First, it enables us to understand how a broad range of batch compositions results in this narrow range of glass compositions. As a consequence, identical base glass compositions do not necessarily reflect a centralized, conservative glassmaking tradition, but can well accord with different glassmaking sites that used similar—though not identical—ingredients and sources of raw materials.

Next, there is the issue of the residual material and the separation of the melt from it. For the time being, one can only assume that this separation was accomplished by simply hand-picking the "good" pieces from the crushed material, and/or by washing this material to remove any water-soluble, unreacted salts and excess compounds. Both mineral soda and plant-ash soda are known to contain variable, but always high, amounts of sulfates and chlorides. Under what were probably non-reducing melting conditions in antiquity, they can be considered unreactive constituents of the batch. Much more work, both archeological and experimental, is needed before one can address this point any further. Some sort of purification or sorting of the primary melting products, followed by a second melting of the selected pieces, would also help to increase the homogeneity of the final glass.

A third point is related to the final ingot-making process and the particular eutectic trough that dominates the base glass composition. As

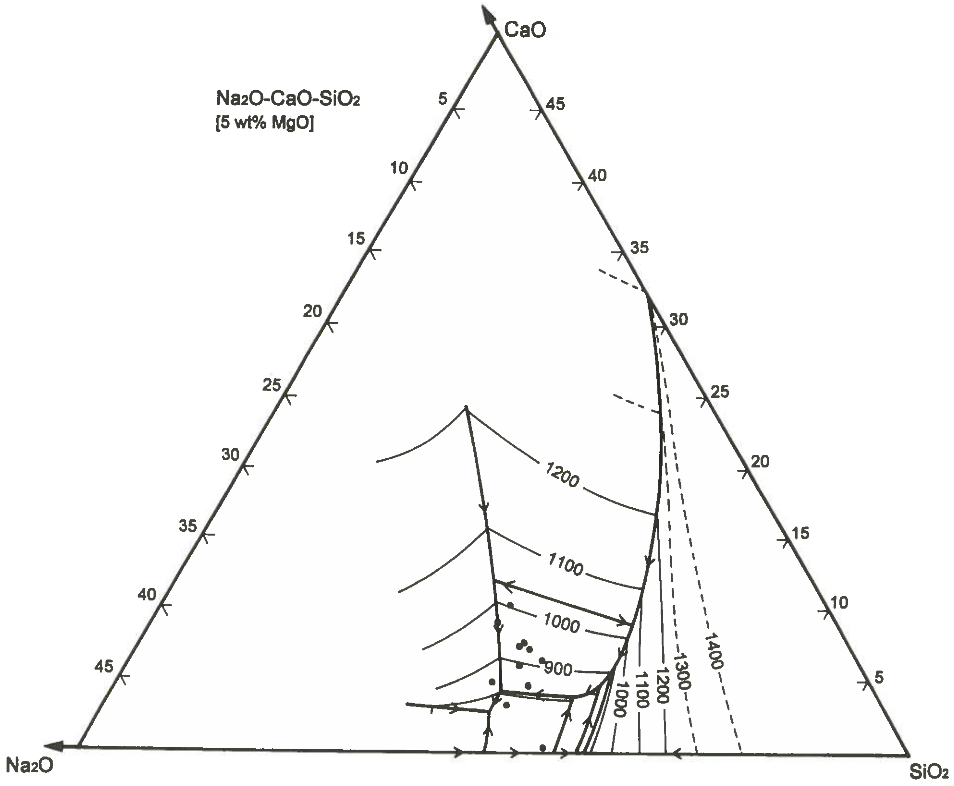

FIG. 2. *Reduced base glass composition of early Egyptian glasses (pre-Amenhotep II). (Original data from C. Lilyquist and R. Brill, eds.,* Studies in Early Egyptian Glass, *New York: The Metropolitan Museum of Art, 1993.)*

has been noted previously,[14] the crucibles used in this operation are internally lined with a thin protective layer of lime. This makes sense only if the glass that is melted in these vessels is saturated with lime at the melting temperature used. Obviously, the NK Egyptian craftsmen were sufficiently aware of this effect to apply this layer of lime deliberately. By contrast, Roman glass was saturated with silica, and the vessels used to melt it were not fitted with an internal lime coating.

A fourth consideration is that the plots of the earlier glasses, attributed to the reigns of Hatshepsut and Tuthmosis III and represented by the first 11 samples in the data set used here, are clearly different from those of glasses that are dated to the reign of Amenhotep II and later (Fig. 2). The earlier compositions show greater scatter than the later ones, and they lie some distance from the eutectic trough. This suggests that these early glasses were manufactured using a "total batch melting" model that relied on the very careful selection of raw materials. It is probably no coincidence that, at the same time that we observe the technological shift from one melting scheme to the other, Egyptologists see a marked increase in the quantity and quality of glass objects: "The reign of Amenhotep II yielded a great deal more glass [than the previous period], of much more sophisticated technol-

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[14] Turner [note 5], Rehren [note 5], Rehren and Pusch [note 5].

ogy, and it displays a high degree of variety and proficiency."[15] The "partial batch melting" model, which afforded the production of better glass in higher quantities from less carefully selected and thus more easily available raw materials, is but one aspect of a much broader progress in glass technology during that period.

The Role of Cylindrical Crucibles in Egyptian Glassmaking

It has recently been shown that it is possible to produce a clear blue mixed-alkali glass ingot high in lime[16] in a single-step crucible melt from a batch made of two parts (by weight) Welsh seaweed ash and one part el-Amarna desert sand, with no further addition of lime.[17] It is proposed here, however, that LBA glassmaking relied on a somewhat different method: making the raw glass in a larger reaction vessel, probably a quartz-lined hearth or open furnace.[18] Only after sorting and selecting the "good" fragments were they loaded into a crucible for remelting and coloring.

For various reasons, the glass is unlikely to have been made in the cylindrical crucibles. First, it would have been highly wasteful of energy to conduct a heat-consuming chemical process in a cylindrical vessel, where the surface of the batch exposed to the heating gases and the radiant heat from the domed superstructure of the furnace would have been particularly small in relation to its volume. Moreover, the heat transfer through the walls would have been inhibited by the insulating ceramic fabric.[19] Second, foaming of the charge as the glass-forming reactions set in would effectively have sealed the top surface against further direct heat input. Third, if the initial glass-forming reactions had indeed taken place within these vessels, one would expect the lime lining of the vessels to have played a role in the reactions. The archeological evidence shows, however, that this was not the case. On the contrary, the reaction of this lime layer with the underlying ceramic fabric is much more pronounced than it is with the glass charge.[20] This indicates that the glass charge melted in the crucibles was already chemically inert against lime and not a chemically active batch of raw ingredients. From all of these observations, it can be concluded that the Egyptian cylindrical crucibles

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[15] Lilyquist and others [note 2], p. 28. I have inserted the bracketed words.

[16] P. Nicholson and C. Jackson, "'Kind of Blue': Glass of the Amarna Period Replicated," in *The Prehistory and History of Glassmaking Technology*, ed. P. McCray and D. Kingery, Westerville, Ohio: The American Ceramic Society, 1998, pp. 105–120. The mixed-alkali formulation is not particularly relevant to LBA Egyptian glasses, but it is likely to develop a melt at even lower temperatures. For a much earlier melt experiment using Middle Eastern ingredients, see Brill [note 3], p. 334.

[17] The replica of the furnace (internal D. 1.5 m), which was able to hold three crucibles similar in size to the archeological ones, was fired for nearly nine hours, and for almost half of that time, the temperature was well above 1100°C. The weight of the glass obtained is not stated, but 380 kilograms of wood was used in producing it. The partial collapse of the furnace prevented a successful run for all of the crucibles. N. Rehder ("High Temperature Technology in Antiquity," in *The Beginnings of Metallurgy*, ed. A. Hauptmann and others, Bochum: Deutsches Bergbau-Museum, 1999, pp. 305–315) remarks that it is often more difficult to hold a furnace down to a desired optimum temperature, in order to prevent damage to the charge and/or to the furnace itself, than to push it up to ever higher temperatures.

[18] Th. Rehren and E. Pusch, "Glass and Glass Making at Qantir-Piramesses and Beyond," *Ägypten und Levante*, v. 9, 1999, pp. 171–180.

[19] Jackson, Nicholson, and Gneisinger [note 4], p. 21. The el-Amarna experiments used two different types of crucibles: a tall, narrow one and a broad, flat one. Only the batch in the flat pot melted entirely, while the tall crucible, charged with the same batch, produced only "a blue frit whilst the lower part had fused to a vesicular, glassy, mass." By contrast, lumps of modern bottle glass that were charged in an identical tall pot and immediately placed next to the other two crucibles "had melted uniformly"; see Nicholson and Jackson [note 16], p. 117. This experiment emphasized the differences in time and temperature required for glassmaking and glass melting.

[20] Rehren [note 5], p. 359.

served to produce colored glass ingots, but not the raw glass from which they were made.[21]

Additional insight into the function of these crucibles—and the processes of Egyptian glassmaking in general—is being provided by ongoing research in the Department of Egyptian Antiquities at The Metropolitan Museum of Art. This research focuses on some technical debris from the Lisht glass factory.[22] Included in the study are two crucible fragments with colored glass preserved on the interior. One of the samples is blue, and the other is purple. In cross section, both fragments show an intermediate layer of colorless glass between the crucible fabric and the colored glass body, and some *schlieren* between the two glass phases, running parallel to the ceramic surface (Fig. 3). This phenomenon, which has also been observed on several other fragments from the Lisht collection, indicates that the glass initially melted in these crucibles was colorless, and that only then was the colorant added to the charge. Whatever mechanism then led to an even dispersion of the colorant failed to include the contact layer. This fact, coupled with the observed *schlieren*, prompts one to infer that the dispersion of the colorant was accomplished by stirring, and not primarily by the dissolution and diffusion of the pigment alone.

Color Characteristics

Despite the homogeneity of the LBA Egyptian base glass composition, several characteristics of specific colors should be discussed briefly. This discussion will focus, not on the colorants themselves, but on minor and trace elements in the glass, the shapes and sizes of ingots (where applicable), and the occurrence at various archeological sites of crucible fragments with adhering remnants of colored glass. My intention here is to identify possible "hallmarks" or "fingerprints" of individual glassmaking factories.

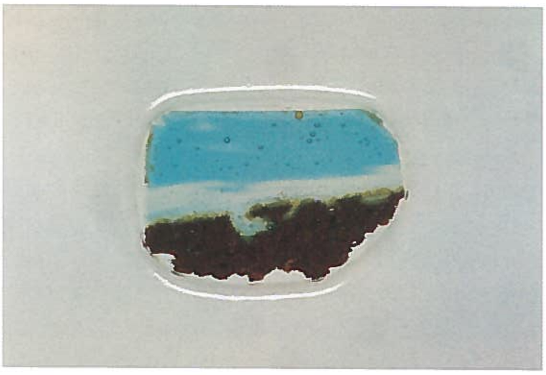

FIG. 3. *Cross section of a crucible wall fragment from Lisht. The blue glass* (top), *colored by copper, is separated from the wall* (dark, bottom) *by a layer of colorless glass. This indicates that the colorant was added only after the glass was melted in the crucible. L. (fragment) about 1 cm. Unaccessioned fragment and sample from The Metropolitan Museum of Art, New York; excavations at Lisht, North Pyramid village. Sample prepared by A. Ludwig, Bochum.*

Cobalt Blue. The colorant used for this glass is cobalt, in the range of a fraction of one percent. The cobalt is typically accompanied by similar amounts of nickel, zinc, iron, manganese, and arsenic, which are believed to derive from the mineral colorant added. The chemical composition of the base glass of this color has long been known to be slightly distinct from that of most other contemporaneous glasses, in that it has significantly more alumina and less potash.[23] While the increased levels of trace elements and alumina are probably due to the ad-

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[21] In the Herat glass factory in 1977, the glassmakers reacted their batches in open mudbrick and clay vessels shaped more like salad bowls than conventional crucible forms. This was done for the same reasons cited above. Personal communication, R. H. Brill, August, 1999.

[22] I am very grateful to Dr. D. Arnold for allowing me to study the collection and to sample some of the finds, and to Marsha Hill and Mark Wypyski for their valuable assistance in doing so.

[23] Lilyquist and others [note 2], pp. 57–58.

dition of the colorant, this does not explain the lower potash level of the glass. This indicates a different provenance for the cobalt-blue glass. There is another unusual feature of this color. P. Nicholson, who was able to take measurements of some of the blue glass ingots excavated from the Uluburun wreck, found a strong correlation between their thickness/diameter and their colorant (copper or cobalt),[24] with the cobalt-colored examples being about twice as thick and significantly larger in diameter than the copper-colored ingots. While the overall shape of the ingots is roughly the same, reflecting the same range of variability in profile as was found in the el-Amarna and Piramesses-Qantir crucibles, the distinct difference in the measurements of the ingots clearly reflects a slightly different workshop practice within a shared technology, namely, using the same crucible type in somewhat different sizes. Crucibles with adhering traces of cobalt-colored glass are known from Petrie's excavation at el-Amarna, although other colors are found there as well.[25] The use of cobalt at that site was not restricted to glass; it was also employed in the manufacture of frit, faience, and a blue-colored ceramic.[26]

Opaque Yellow. This color is most commonly used as a decoration on blue glass objects, but it is rarely found on its own. Early on, it attracted the attention of scientists for its colorant, lead antimonate.[27] While antimony is commonly found in opaque glasses of that period, opaque yellow glass is differentiated from other colors primarily by its lead content. There are other differences as well. Five of the six analyzed samples in the data set in which the SO_2 level is given as "0"[28] are opaque yellow, while all but one of the other samples, whether or not they are opaque, have sulfur dioxide concentrations of about 0.4 percent by weight.[29] The low antimony content of these five glasses (on average, 0.8% Sb_2O_5, while the average of the other 23 opaque glasses is 1.85%) is noteworthy in that lead antimonate is the pigment for these opaque yellow glasses. A low antimony content in opaque yellow glass is also found in the Brookhaven data,[30] with an average of 0.6% in the three yellow glasses and an average of 1.6% in the other 14 second-millennium B.C. samples, and this suggests that the readings are not due to analytical problems. Unfortunately, there is little archeological evidence for the making of this yellow glass. Recently, lumps

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[24] Nicholson, Jackson, and Trott [note 5]. See also Th. Rehren, E. Pusch, and A. Herold, "Glass Coloring Works within a Copper-Centered Industrial Complex in Late Bronze Age Egypt," in *The Prehistory and History of Glassmaking Technology*, ed. P. McCray and D. Kingery, Westerville, Ohio: The American Ceramic Society, 1998, pp. 227–250, esp. p. 245, fig. 8.

[25] In an e-mail message dated October 13, 1998, P. Nicholson confirmed the impression I had formed from studying some of Petrie's material in London and Oxford.

[26] A. Shortland and M. Tite, "The Interdependence of Glass and Vitreous Faience Production at Amarna," in *The Prehistory and History of Glassmaking Technology*, ed. P. McCray and D. Kingery, Westerville, Ohio: The American Ceramic Society, 1998, pp. 251–265; J. Riederer, "Recently Identified Egyptian Pigments," *Archaeometry*, v. 16, 1974, pp. 102–109; H.-G. Bachmann, H. Everts, and C. Hope, "Cobalt-Blue Pigment on 18th Dynasty Egyptian Pottery," *Mitteilungen des Deutschen Archäologischen Instituts in Kairo*, v. 36, 1980, pp. 33–37.

[27] W. E. S. Turner and H. Rooksby, "A Study of the Opalising Agents in Ancient Opal Glasses throughout Three Thousand Four Hundred Years," *Glastechnische Berichte*, v. 32K, 1959, pp. VIII/17–28.

[28] See Lilyquist and others [note 2], table 2, nos. 3, 21, 26, 30, and 35.

[29] However, one would like to know (e.g., by means of wavelength dispersive spectrometry) whether this apparent absence of sulfur is simply a measuring artifact of the EDS system used, the sulfur peak being effectively superimposed by the close-by and more dominant lead peak.

[30] E. Sayre, "Some Materials of Glass Manufacturing in Antiquity," in *Archaeological Chemistry*, ed. M. Levey, Philadelphia: University of Pennsylvania Press, 1967, pp. 279–311.

of yellow glass were found off the coast of Israel, but no further context for them is known.[31] The lead isotope signature of the yellow glasses from the reign of Amenhotep II and later[32] indicates a possible Egyptian origin for the lead, if not for the entire glass, but no archeological site has yet been found in which there are fragments of cylindrical crucibles with yellow glass adhering to them.

Copper Blue. This is the most commonly used color in Egyptian glass objects. It could thus be considered the "standard" colored glass of that period, against which to compare all other finds. This need not be the case, however, since we have evidence for the making of copper blue glass ingots from a range of sites, including el-Amarna, Lisht, and probably even Piramesses-Qantir.[33] Therefore, there may well be different varieties of this material, reflecting different places of production.[34] As was noted earlier in connection with the cobalt blue ingots from Uluburun, the five copper-colored ingots from that site, measured for thickness and diameter by P. Nicholson, plot close to one another, and they are clearly different from the cobalt blue ingots. This suggests that they derive from a single source, separate from the source of the cobalt blue ingots. It is not yet possible to attribute these ingots to a specific archeological site. The copper-colored blue ingot fragment from Lisht, which is likely to have been made there, has a significantly larger diameter, and is probably of a later date than the Uluburun cargo.[35]

Copper Red. Scientists are particularly interested in this color because of the considerable skill that was required to produce it.[36] It has been noted in greater detail elsewhere that the Ramesside site of Qantir in the Nile Delta seems to have produced copper red glass in the broader context of a copper-centered industry.[37] Interestingly, this type of glass contains the same level of antimony as most of the other opaque glasses, although the very nature of its pigment (i.e., discrete particles of cuprite) renders the glass opaque anyway. This raises the question of when, why, and how the opacifying antimony was added to the glass.

Patterns of Glassmaking in LBA Egypt

The archeological evidence and the analytical data accumulated during the last 10 years allow us to draft a new model for LBA glassmaking in Egypt. It appears very probable, for example, that raw glass was made in ancient Egypt, based on crucible finds at relevant sites (e.g., el-Amarna, Piramesses, and Lisht) and archeological evidence for possibly related furnaces at el-Amarna and Piramesses. Such evidence is still lacking for Mesopotamia, although this is likely due to the absence of excavation

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[31] E. Galili, U. Dahari, and J. Sharvit, "Underwater Surveys and Rescue Excavations along the Israeli Coast," *The International Journal of Nautical Archaeology*, v. 22, 1993, pp. 61–77.

[32] R. Brill and others, "Lead-Isotope Analyses of Some Objects from Egypt and the Near East," in *Studies in Early Egyptian Glass*, ed. C. Lilyquist and R. Brill, New York: The Metropolitan Museum of Art, 1993, pp. 59–75.

[33] No crucible fragment with adhering copper blue glass has been found at Qantir. However, there is one lump of copper blue glass, which may indicate that the color was made locally; see Rehren [note 5], pp. 361–363.

[34] For a comparison of blue glasses worked at Malkata and Lisht, see C. Keller, "Problems in Dating Glass Industries of the Egyptian New Kingdom: Examples from Malkata and Lisht," *Journal of Glass Studies*, v. 25, 1983, pp. 19–28, esp. p. 26, which notes distinct differences in color, opacity, and general quality between the two.

[35] For the dating of the Lisht material, see Keller [note 34]. For the Uluburun wreck, see Pulak [note 6], p. 257.

[36] Turner and Rooksby [note 27]. For additional discussion, see Freestone [note 2]; and R. H. Brill and N. D. Cahill, "A Red Opaque Glass from Sardis and Some Thoughts on Red Opaques in General," *Journal of Glass Studies*, v. 30, 1988, pp. 16–27.

[37] Rehren, Pusch, and Herold [note 24].

there. In view of the early occurrence of glass in Mesopotamia, a local glass industry there is highly probable. The idea that there may have been several coexisting centers of glassmaking in LBA Egypt and the Middle East is not contradicted by the apparent chemical homogeneity of the glass artifacts, which can be explained by the "partial batch melting" model developed above.

There is also a strong indication that specific colors were made only at certain sites, such as red at Piramesses and probably cobalt blue at el-Amarna, and yellow and white glass is thought to have been made at other, yet unidentified locations. Copper blue glass was probably made at all of the known sites, but colors that required either exotic colorants (e.g., cobalt and manganese) or specialized knowledge (e.g., cuprite red and lead antimonate yellow) are believed to have been made at only one or two sites. Such specialization appears to have been based mainly on the available supply of the materials required, reinforced by the know-how to work them.

It should be emphasized that this idea of glass specialization on the basis of colors is still conjectural and applies solely to the *making* of colored glass. The *working* of glass at each of the known sites typically encompassed the entire range of available colors. As has long been known by Egyptologists,[38] each of these artistic workshops had its own stylistic characteristics, which reflected the skills and the preferences of the artists employed there. This workshop tradition is separate from the factory tradition proposed here for the making of raw and colored glass.

Concerning the organization of the glass industry, the making of glass is supposed to have been distinguished—in terms of activities, locations, and the labor force required—from the artistic working of objects. The use of various colors at any one workshop indicates an active long-distance trade network for colored glass, and both the Uluburun cargo and the Amarna letters provide good evidence for such a network. Sites such as Malkata, el-Amarna, and Lisht may have hosted glassmakers as well as glassworkers, while at Piramesses we have evidence only for the making of red ingots and flat glass for inlay work, and not for the artistic production of polychrome objects.

Suggestions for Further Research

This article has noted the intriguing difference, as to position within the phase diagram and in terms of quality and quantity, between the very early glass used in Egypt and the artifacts produced during the reign of Amenhotep II and later. In the former group, the ratio of alkali oxides to silica reveals more silica-rich compositions, and the ratio of potash to soda is significantly different from the later examples (on average, 3.2 wt % K_2O and 18.3 wt % Na_2O, as compared with 2.3 wt % and 19.4 wt %, respectively, in the later glasses, using data from non-cobalt glasses only). While the total alkali-to-silica ratio probably reflects a different batch melting technique, the soda-to-potash ratio should indicate the use of different plants. Inland sources probably yielded higher potash values, while lower potash concentrations could be expected to point to coastal or soda-dominated desert oasis areas. Is it likely that these two sources were Mesopotamia and Egypt?

The difference is further underlined by the lead isotope signature of the one pre-Amenhotep II opaque yellow glass analyzed to date. It suggests a Mesopotamian origin, while the later yellows are in accordance with Egyptian

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[38] B. Nolte, *Die Glasgefässe im alten Ägypten*, Münchner Ägyptologische Studien, v. 14, Munich, 1968.

lead.[39] It will be very interesting to see whether these differences are supported by additional analyses, involving more material from both Mesopotamia and Egypt,[40] and whether this eventually allows us to determine the provenance of the early Egyptian glasses on the basis of trace or minor element concentrations and stable isotope ratios.

Similarly, we can look forward to the eventual determination of a provenance for the various color characteristics of the glasses made during the reign of Amenhotep II and later. In particular, this should help us understand the relationship between glassmaking factories as suppliers and glass workshops as consumers of colored glass. C. Keller alludes to differences in quality and access to raw materials between the courtly sites of Malkata and el-Amarna and the village site of Lisht.[41] This relates directly to the broader question of patterns of control over crafts and materials in Egypt.

Closely related to the question of site specialization for specific colors of glass is that of the integration of the glassmaking industry with other high-temperature crafts and technologies. The prime candidates for this kind of research are again el-Amarna[42] and Piramesses-Qantir,[43] but a review of other sites may prove valuable here as well.

Finally, the still enigmatic process of making raw glass requires much more scientific and technical research, including archeological work that centers on factory sites rather than on temples and graves.

APPENDIX

Data Processing and Reduction

In order to plot multidimensional data into a ternary diagram, one has to reduce the number of variables to three. For the base glass composition, consisting of seven oxides, this was achieved by combining silica, alumina, and iron oxide to silica, by combining soda and potash to soda, and by combining lime and magnesia to lime. To compensate for the different molecular weights, individual correction factors were applied to the minor oxides before adding them to the major compound (namely, 0.60 for alumina and 0.75 for iron oxide to get s[illegible]a, 0.66 to transmute potash into soda, and 1.39 to change magnesia into lime). Alumina, iron oxide, and potash concentrations were thus mathematically reduced to zero. In order to match the constant basic level of 5 wt % magnesia of the quasi-ternary diagram chosen here, the actual magnesia level found in each sample was adjusted to 5% either by topping up with lime or by transferring excess magnesia into lime. In order to match the ternary diagram presented by Shahid and Glasser,[44] these intermediate data then had to be renormalized to 95%.

The application of phase diagrams to archeological materials has many inherent problems. For one, phase diagrams aim to represent equilibrium conditions, while, more often than not, archeological processes operate off the equi-

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[39] R. Brill (*Chemical Analyses of Early Glasses*, Corning, New York: The Corning Museum of Glass, 1999, v. 1, p. 280) notes the similarity of some (unspecified, but undoubtedly those mentioned here) pre-Malkata glasses and the Mesopotamian Nuzi glasses, which probably date to the 15th or 14th century B.C. For a detailed discussion of the lead isotope data, see Brill and others [note 32], pp. 63–64.

[40] R. H. Brill's monumental work, *Chemical Analyses of Early Glasses* [note 39], appeared only after this study was completed. The additional data now available will further our understanding of ancient glassmaking almost worldwide, and will certainly underline the preliminary character of this pilot study.

[41] Keller [note 34].

[42] Shortland and Tite [note 26].

[43] Rehren, Pusch, and Herold [note 24].

[44] Shahid and Glasser [note 9].

libriums but preserve metastable conditions or even semi-finished chemical reactions. In addition, the reduction of multidimensional data to fit into a quasi-ternary diagram necessarily results in both loss of information and biased results. For the extent of such a bias, the reader is invited to compare Figure 1 of this article with figure 6 of a publication I co-authored in 1998,[45] in which the soda-lime-silica diagram without a flat rate of magnesia was used on the same set of data, but otherwise reduced in the same way as in the current article. The data set fell significantly to the left of the trough, instead of hitting it, and at a clearly higher range of temperatures. With no reliable data on hand as to the influence of 1% each of alumina, potash, and iron, and with a deviation of up to 1% from the fixed 5% magnesia level on the shape of the liquidus surface discussed here, one can only hope that these influences either are small or negate one another at least in part. As a general rule, however, the addition of small amounts of other oxides should reduce melting temperatures, as has been shown experimentally for potash, iron, magnesia, and alumina. Chlorine should act similarly.[46] The greatest source of uncertainty thus remains with the colorants, which by no means simply dilute the batch, but influence the melting behavior in several ways: (1) modifying the internal heat absorption, transfer, and radiation properties due to the selective absorption (or non-absorption) of particular wavelengths, (2) increasing melt viscosities and thus reducing heat diffusion rates due to abundant nucleation, and (3) actively entering into the glass network. Here is where we face our biggest problems when reducing the raw data, but we have no solution to date except to be especially careful in our interpretation of the data.

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[45] Rehren, Pusch, and Herold [note 24], p. 241.

[46] For more discussion of these effects and a proposed thermometry model based on the chlorine content of the glass, see Rehren [note 10].