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Contextualizing the Archaeometric Analysis of Roman Glass

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Contextualizing the Archaeometric Analysis of Roman Glass

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Abstract

This thesis is a review of recent archaeometric studies on glass of the Roman Empire, intended for an audience of classical archaeologists. It discusses the physical and chemical properties of glass, and the way these define both its use in ancient times and the analytical options available to us today. It also discusses Roman glass as a class of artifacts, the product of technological developments in glassmaking with their ultimate roots in the Bronze Age, and of the particular socioeconomic conditions created by Roman political dominance in the classical Mediterranean. The principal aim of this thesis is to contextualize archaeometric analyses of Roman glass in a way that will make plain, to an archaeologically trained audience that does not necessarily have a history of close involvement with archaeometric work, the importance of recent results for our understanding of the Roman world, and the potential of future studies to add to this.
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Section 1: General Introduction

Archaeometry, broadly defined, is the application of analytical techniques and expertise derived from the “hard” sciences (biology, chemistry, and physics, though the term is most closely linked with chemistry) to the study of archaeological materials. Scientists have performed compositional analyses of artifacts since the earliest days of archaeology in the 18th and 19th centuries, though this early work was often without any clear direction beyond simple curiosity about the chemical makeup of different materials, which in many cases was not well established at the time. Systematic, rigorous work in the field is largely a product of the second half of the 20th century. Undoubtedly the most famous of the archaeometric methods pioneered in this period is radiocarbon dating, which for the first time allowed archaeologists to assign calendar dates to artifacts, independently of any historical records. Other well-known types of archaeometric study include compositional analysis of pottery to determine the geological source of its raw materials, and organic residue analysis to determine the contents once held by vessels. In spite of its transformational effects on the last sixty years of archaeology, archaeometry’s methods are often poorly understood by archaeologists. Archaeometrists and archaeologists attend different conferences, publish in different journals, and (especially in North American institutions, less so in Europe) are members of different university departments. This is particularly true in classical archaeology, which is more closely tied to historical and literary scholarship of Greek and Roman civilization than it is to other archaeological fields, and is doubly reluctant to embrace a “scientific” viewpoint.
The present work aims to review recent archaeometric studies on a single class of archaeological material, namely glass, in a single historical period, that of the Roman Empire. It breaks no new ground in archaeometry; it presents no new technique, nor any methodological improvement to an existing one. Classical archaeologists are its intended audience; an understanding of how the chemistry of glass can be related to cultural, and economic phenomena surrounding glass production is its intended effect. To this end, Roman glass will be discussed both as a material, with particular physical and chemical properties, which lend it to certain practical applications and certain types of modern analysis; and as a class of artifacts, the product of technological developments in glassmaking with their ultimate roots in the Bronze Age, and of the particular socioeconomic conditions created by Roman political dominance in the classical Mediterranean. This review is divided into six sections, sections 1 and 6 being, respectively, this introduction, and some concluding remarks. A glossary of scientific and glass-related terminology is also included, following the conclusion.

Section 2, “Glass as a Material,” describes the physical and chemical properties of glass, and how they relate to its manufacture and use in ancient societies. An understanding of the basic chemistry of glass, and how this is affected by each of its main ingredients, is necessary to engage properly with the compositional analyses that are the most common application of archaeometric techniques to glass studies. The unusual molecular structure of glass is also important to understand, as it is responsible for the properties that make glass unique as a craft material in the ancient Mediterranean, as well as for some of the key practical differences between chemical analyses of glass and pottery. This section also includes descriptions of the major
craft techniques in use for the production of glass vessels in the ancient world, and the methods by which glass was made from its raw materials.

Section 3, “The History of Glassworking and Roman Sources on Glass,” gives some of the historical context of the Roman glass industry. The Romans are remembered in the glass industry today for the revolutionary introduction and popularization of glassblowing, and the transformation of glass from a luxury good into one of the trappings of the “middle class.” As we shall see in this section, glass had been made in the Mediterranean for over a thousand years before the Roman Empire came to dominate the region, and the age of the tradition makes its sudden invigoration in the first few decades of the Imperial period all the more striking. This was not lost on our most important extant literary source for Roman glassmaking, the polymath encyclopedist Pliny the Elder, whose thoughts on the subject are also discussed here. Understanding the history of the glass industry before the Roman Empire, and of its continuation into the Byzantine period, allows us to appreciate the significance of the technological and economic changes in glass production that occurred under Roman rule, and how the questions discussed in the following section fit into the broader context of ancient glass production.

Section 4, “Current Issues in Glass Analysis,” describes the basic principles of the analytical techniques most commonly applied to the study of archaeological glass today, and explains their respective advantages and applications in archaeology. These descriptions do not aim to provide in-depth critique of technological methodology, and likely contain little that will be of interest to a seasoned archaeometric researcher; they are intended to help readers from a more traditionally
archaeological background to engage with archaeometric issues. This section also reviews the chemical evidence that has been used in recent attempts to determine the sources of raw materials and the locations of primary production in the Roman glass industry. Work in this area largely follows the precedents set by similar analysis of pottery. However, it faces added complications due to the two-stage process of glass manufacture, whereby the fusion of raw glass from natural materials (primary production) often occurs in a completely different location to the manufacture of glass vessels from blocks or chunks of glass (secondary production). The bulk of this section focuses on the question of where most primary production took place in the Roman Empire.

Section 5, “The Historical Importance of Glass Analyses,” discusses the place of archaeometry generally, and glass analyses in particular, in archaeological endeavors, and attempts to show how chemical analysis of Roman glass can contribute to more “mainstream” archaeological questions about cultural change. Archaeometry, particularly in classical studies, is plagued by accusations of irrelevance, and limited by poor integration of its contributions into modern interpretative models for understanding ancient cultures. Achieving greater experimental accuracy and precision, or inventing innovative new techniques for analyzing archaeological materials, is ultimately of little use to anyone unless archaeologists can be convinced that archaeometric methods offer unique, valuable insights into the ancient cultures they study. Archaeometry is at its best when archaeologists take an active role in planning analytical strategies and interpreting results. This final section offers some initial suggestions on how to see archaeometric studies of glass in the wider context
of Roman archaeology, and on further questions that future studies might attempt to answer.

Ultimately, this review aims to give context to archaeometric studies of Roman glass. Archaeological materials can be studied from several perspectives, and each implies a different context: the different purposes to which a single culture puts different materials; how the use of a single material varies from one civilization to another; how cultural use of a material relates to environmental factors. Investigators from different disciplines will naturally be drawn to view artifacts in one context or another. A Roman archaeologist may see a glass bottle as an example of a Roman vessel, and compare it to a pottery equivalent. A glassblower may see it as an example of ancient glass technology, and compare it to an Egyptian design. A geochemist may see it as an example of the exploitation of a particular sand source or colorant, and compare it to a glass with a different composition. Obviously, no one scholar can fully embrace all relevant branches of knowledge. However, awareness of multiple possible contexts, and willingness to look outside traditional disciplinary boundaries, broadens the range of insights available to us. The existence of a body of archaeometric knowledge relating to glass is just the first step. Only by engaging with this work on its own terms, and giving sustained consideration to its relationship with our own, can archaeologists reap the full benefits of modern technological approaches to glass studies.
Section 2: Glass as a Material

Introduction

In any archaeometric study, it is important to begin from a sound understanding of the physical and chemical properties of the material under discussion. These properties influence both the way the material was used in the ancient world, and the way it was perceived by those using it. Glass, once it has been worked, resembles pottery in a number of important respects that result from its chemical nature; while actually being worked, it is more reminiscent of, if anything, molten metal, but behaves somewhat differently for reasons related to its molecular structure. It also has properties that resemble neither, which in the ancient world would have recommended themselves most easily to comparison with precious stones (namely color, or lack thereof, and transparency). This section will explore the physical and chemical nature of glasses (both man-made and naturally occurring), describing how their properties shaped their use in antiquity, and dictate the avenues of chemical analysis open to us today.

Structure and Physical Properties of Glass

Most archaeologists would not think of glass when they hear the word “ceramic,” which in our discipline is normally reserved for pottery. In the physical sciences, however, glass is regularly described as a ceramic material, and in many important respects it does resemble pottery. Ceramics, in engineering and materials science, are simply inorganic, non-metallic solids; the term is normally applied only to man-made
materials, and is most commonly used of those treated with extreme heat during the manufacturing process.¹ They generally have very high yield stress (that is, it is extremely difficult to bend, stretch, or otherwise permanently deform them); they tend to be good insulators against both heat and electricity; and they are generally resistant to corrosion and biodegradation, hence the proverbial “indestructibility” of pottery sherds.² On the other hand, ceramics are also heavy compared to organic materials like wood, while being much more brittle than most metals, and are highly vulnerable to thermal shock (the mechanical stress brought on by rapid temperature changes – many of us will be familiar with this phenomenon from experiences with glassware in our own kitchens).

In the modern world, the general imperviousness of glass to water, corrosive chemicals, and microorganisms ensures its prevalence in drinking, storage, and laboratory wares; its transparency is also vital to a wide variety of optical applications, and its resistance to electricity is often put to productive use. In the ancient Mediterranean, prior to the Imperial Roman period, glass is outcompeted in most utilitarian functions, such as transport and storage, by cheaper, more readily available pottery, which shares most of its virtues. Instead, it is mainly reserved for luxury items, of which there are many spectacular examples, particularly from the Late Bronze Age and the Hellenistic period, which exploit the full range of vibrant colors that can be produced in glass by means of mineral pigments (see below). However, technological developments of the late Hellenistic and early Imperial periods (see section 3) significantly reduced the price of glass, and increased the

¹ Le Bourhis 2014, p. 7. Most glasses do contain metal atoms, but they do not display the delocalised form of atomic bonding that is characteristic of true “metallic” solids.
available range of sizes and forms. As a result, glass became a viable alternative to pottery for a wide variety of utilitarian functions, despite almost certainly still being more expensive, perhaps because it was also cleaner and less porous.\textsuperscript{3} Glass windowpanes became common during the first century A.D., though their quality varies wildly; it has been suggested, based on comments made by Vitruvius (\textit{De Arch} 6.4) that the Romans thought of glass windows mainly as a way to let in sunlight while retaining heat, and were usually unconcerned with their ability (or lack thereof) to provide a view.\textsuperscript{4} By the 2\textsuperscript{nd} century A.D., if not earlier, the optical properties of glass were also greatly appreciated by Alexandrian scientists for their experiments, though these were, of course, niche uses.\textsuperscript{5} Glass mirrors seem to have existed, and a few archaeological examples are known, but polished metal remained more common throughout antiquity.\textsuperscript{6}

What distinguishes a glass from other chemically related materials, including pottery, is the degree of molecular-level order exhibited by the substance. For instance, the soda-lime glass produced in the Roman Empire (as well as in modern industry) is mostly made up of the same molecular-scale repeating units as quartz, a crystalline form of silica (SiO\textsubscript{2}); namely, SiO\textsubscript{4} tetrahedra, chemically bonded together in a continuous network of atoms. In quartz, and other “crystalline” solids, these “building blocks” are found in ordered, symmetric arrays that repeat themselves on a broad, sometimes macroscopic scale (see figure 2.1), such that, in a hypothetical

\textsuperscript{3} Stern 1999, p.479.
\textsuperscript{4} Fontain and Foy 2005, p. 17; Stern 2007, p. 386; but see also Leary 2011 on the clarity of window glass.
\textsuperscript{5} Stern 2007, pp. 379-382.
\textsuperscript{6} Leary 2011, p. 236
perfect crystal, it would be possible to predict the positions of every single atom. In silica glasses, on the other hand, the arrangement of the tetrahedra with respect to one another is all but random, and there is no long-range regularity or symmetry (see figure 2.2). Solids like this are said to be “amorphous.” It is this lack of order that gives rise to most of the unique properties of glasses, and the features that differentiate them from pottery from a craft perspective. A wide variety of other amorphous materials can be referred to in structural chemistry as “glasses” or “glassy solids,” including a wide variety of plastics, and even, in recent years, certain specially prepared metal alloys. However, these materials are modern inventions, and of strictly tangential interest here.

Figure 2.1: A two-dimensional approximation of the three-dimensional network of SiO$_4$ tetrahedra that makes up the structure of crystalline silica. After Le Bourhis 2014, p. 58.

Figure 2.2: A similar approximation of the structure of glassy (“fused”) silica. Note that the SiO$_4$ tetrahedron remains the base unit, but that the arrangement of tetrahedra becomes irregular. After Le Bourhis 2014, p. 58.

The erroneous belief that glasses are “technically liquids,” regularly encountered in popular literature or high school science, stems from their near-total lack of

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7 Le Bourhis 2014, p. 56.
8 Le Bourhis 2014, pp. 66-68.
molecular-level structure.\textsuperscript{9} While such a description is misleading, it probably stems from a real scientific fact: a glassy solid’s lack of long-range order is in some ways reminiscent of the interaction between molecules in a true liquid. In liquids, molecules remain in contact with one another (rather than flying apart completely, as in a gas) and influence each other’s movement, but any patterns they form are short-ranged and incidental. Indeed, in the physical sciences liquids are often used profitably as an analogy for glasses, describing glass as “a frozen liquid for which viscosity becomes so high that the atomic motions have slowed to the extent that characteristic relaxation time exceeds the observation period.”\textsuperscript{10} The molecular structure of a glass is not unlike a “snapshot” of the shifting, chaotic arrangement of molecules in a liquid at a single point in time, frozen in place by relatively rapid cooling.

Because of the irregularity of their structure, glassy solids do not have clearly defined melting points as conventional crystalline solids do; nor can a glassy solid be formed simply by decreasing a liquid’s temperature below a clearly defined freezing point. Instead, they pass slowly from a solid state to a true liquid state over a range of temperatures, sometimes comprising several hundred degrees Celsius, within which the material loses its rigidity, and gradually becomes less and less viscous. Different viscosities, and therefore different temperature ranges, are suitable for different stages of the glassworking process. This gradual transformation begins at the so-called “glass transition temperature” ($T_G$), the point at which atoms and molecules in the

\textsuperscript{9} See Brill 2011, 29 September for a discussion of the myth, including the common misconception that Mediaeval window glass can be observed to have slumped downward in its frames over the centuries.

\textsuperscript{10} Le Bourhis 2014, p. 8.
glass have enough energy to rearrange themselves relative to each other (this is itself a variable figure, dependent on the speed at which the original glassy solid was cooled from a melt, but in the case of soda-lime glass is typically about 500 ºC). The transformation could be said to end at the melting point of the corresponding crystalline solid, by which point the substance is undeniably a liquid. In polymer science, the pliable intermediate between a glassy solid and a true liquid is referred to as the “rubbery state.” This term is not normally used of ceramic glasses, since the structure of polymers is a more complicated matter with its own peculiarities, which are not directly comparable. Nonetheless, the image evoked by it has some illustrative utility.

To produce glass lumps, slabs, chips, or dust, suitable to be worked into vessels or other items by artisans, it is first necessary to destroy the crystalline order of the raw ingredients, by raising the materials to a temperature at which they are completely liquid (the “liquidus temperature,” $T_L$). For the particular mixture of ingredients that make up most Roman glass, this temperature is on the order of 1100 ºC (see below). If, as commonly happens in the case of silica-rich materials in nature, the melt is allowed to cool very slowly, new crystals will grow from the semi-liquid glass. Below $T_G$, atoms and molecules in the glass are “frozen” in their disordered state, and cannot rearrange into a crystalline structure; by contrast, above $T_L$, crystalline form is not thermodynamically favored; between the two, especially close to $T_L$, crystallization is possible. In glassmaking, this is highly undesirable, and a significant amount of research today is devoted to minimizing crystallization in industrial processes.\footnote{Le Bourhis 2014, pp. 68-76.} However, it is difficult to assess the extent to which crystallization was
serious problem for ancient glassmaking processes, due to a shortage of material evidence for primary glassmaking (see section 4).

Another hazard necessitating some degree of temperature control is that glass is particularly liable to suffer thermal shock while finished pieces are cooling. Above \( T_G \), because atoms within the glass still have some freedom of motion, internal stresses in the material will relax over time. However, once an object cools below \( T_G \), and the structure “freezes,” stress patterns freeze with it, and can weaken or crack the glass. For this reason, modern glassworkers will hold a finished piece of glass slightly above \( T_G \) for hours or days, sometimes even weeks for large objects, a process known as annealing. This allows time for atoms to make small movements of relaxation, relieving internal stresses, without providing enough heat to permit crystallization. If an object has not been properly annealed, regions under this kind of residual stress are visible when viewed under cross-polarized light. Breaking an object tends to relieve mechanical stresses in the material, so routine examination of archaeological materials in this way is not particularly productive, but it is a potential non-invasive analytical option for objects that are recovered intact (e.g. from tombs). Robert Brill observed that ancient glass artifacts tend to show evidence of strain at the joining points of trails, blobs, and handles, where hot glass would have been applied to glass that was already quite cool, but are otherwise mostly free of internal stress.\(^\text{12}\) This suggested to him that glassworkers in the ancient world were normally capable of annealing glass objects reasonably well. However, it seems likely that a large proportion of poorly annealed vessels would have failed shortly after being finished, in which case the broken glass would simply have been recycled by the workshop,

\(^{12}\) Brill 1988, pp. 280-281.
never entering the archaeological record. Moreover, it is unclear whether Roman glassblowers used separate annealing ovens, whose temperature could be controlled independently.\textsuperscript{13} It is therefore difficult to say how clearly Roman glassworkers understood annealing, or how well they could control the process, though they almost certainly did appreciate that glass vessels had to be cooled to room temperature very slowly.

The lack of molecular-level order in a glassy solid is responsible for perhaps the most striking physical trait of glass: its transparency, a characteristic that would have held significant novelty value for ancient cultures used to drinking from pottery vessels. A piece of quartz, large enough to be held in the hand, may be made up of thousands of crystal domains with the same internal structural principles but different geometric orientations. Between any two crystalline domains exists a plane of discontinuity that will refract any light passing through it. When light must pass through many such discontinuities, it is scattered in all directions; for this reason, crystalline objects are generally opaque, unless composed of a single, very large crystal. Glass, on the other hand, because its structure has little to no order, can have no discontinuities either – the irregular nature of the solid is continuous and unvarying. This minimizes scattering, so that light passes through glass objects with only minor refraction. If desired, glass can be rendered opaque by adding crystalline colorants to the mixture, or by reheating the glass above $T_G$ after it has been worked, and holding it at a high temperature long enough for crystallization to occur.\textsuperscript{14} Translucent and transparent

\textsuperscript{13} Henderson 2013, p. 229.
\textsuperscript{14} Henderson 2013, p. 4. The former method is common in antiquity; the latter seems not to have been.
glasses are generally favored in the Roman world. Opaque glasses are more common in earlier periods, though they never actually disappear.

**Techniques for Working Glass**

The continuous nature of its transition from a rigid solid to a pliable solid to a viscous liquid is at the heart of most techniques for manipulating the material. Four common techniques dominate assemblages of ancient vessel glass: core-forming, slumping or sagging, casting, and blowing. The use of these techniques throughout antiquity will be covered in section 3, but it seems appropriate to include some description of their physical aspects here. Furnace and kiln structure are also in need of brief discussion.

The first glass vessels of the Late Bronze Age were made by a technique known as core-forming, based on roughly shaped solid clay molds. The molds were wetted, packed with glass dust, then heated until the dust fused; additional layers of glass dust
would stick to the hot glass, allowing the process to be repeated until the walls of the vessel were built up to the desired thickness (see figures 2.3, 2.4 and 2.5). Vessels made using this method were commonly decorated by winding pre-formed rods of hot glass in contrasting colors around the outside of the vessel, then dragging with a pointed tool to create zig-zag or feather patterns. Once the glass had cooled, the clay mold could be scraped out (obviously a somewhat laborious process, given that core-forming mostly produces closed shapes). The patterns of cracking visible in some monochrome core-formed pieces imply that sometimes entire vessels, not just the decorative elements, were made using coiled rods rather than layers of glass dust; this method may have been standard during the historical period. Core-forming remains an important technique for working luxury vessel glass well into the Hellenistic period. Thereafter, it begins to be eclipsed by more efficient methods, and core-formed glass is rare in Roman times.

Glass can be cast in a mold, as metals can, though the specifics of the technique were likely different, because molten glass, unlike molten metal, rapidly becomes more viscous as it cools, and is therefore very difficult to pour evenly. Modern furnaces can keep glass hot enough to

Figure 2.6: A particularly brilliant example of cast mosaic glass in the Corning Museum of Glass, early 1st century B.C., find spot unknown. After Harden 1987, p. 35.

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do this practically, but there is some doubt as to whether ancient furnaces could, especially prior to the Imperial period.\textsuperscript{18} Most cast glass in antiquity was probably chip-cast, filling a mold with chips of glass or partially reacted sandy material (known in the industry as “cullet” and “frit,” respectively), before fusing the glass in a furnace. Combining chips of different colors, or slices of prefabricated glass canes, can produce patterned “mosaic” glasses (see figure 2.6), like the spectacular dishes and bowls of the early Hellenistic Canosa group.\textsuperscript{19} Archaeologists are advised to use caution in reading descriptions of “cast” glass. Some glass specialists have argued that the term is overused, and it has at times been used to refer to any glass object that is neither obviously blown, nor decorated in the zig-zag style most famously associated with core-forming.\textsuperscript{20} Many such “cast” objects may, in fact, be slumped or core-formed.

Slumped or sagged glass is made by heating a pre-formed disk or slab in a kiln, over an open or inverted mold. Once the glass is no longer rigid enough to support its own weight (around 700-750 °C), it slumps over an inverted mold (see figure 2.7), or sags into an open one (see figure 2.8). The earliest known examples of slumped glass in the Mediterranean come from the Classical period.\textsuperscript{21} While glassblowing would eventually offer improved efficiency with raw

\textsuperscript{18} Lierke 2002, p. 183; Stern 2007, p. 348.
\textsuperscript{19} Harden 1968.
\textsuperscript{20} Lierke 2002, p. 185.
material, and greater freedom of form, slumping and sagging are significantly faster ways of shaping glass than earlier techniques, and require less skill than core-forming. These advantages may have contributed to the mass production of slumped monochrome glass bowls in the Hellenistic kingdoms, the first known instance of mass-produced glass anywhere in the world.\footnote{Henderson 2013, p. 212.}

Blown glass is glass that has been inflated by breath using a blow-pipe – a revolutionary way of manipulating the material, probably invented in the first century B.C. in the Syro-Palestine region.\footnote{Israeli 1991.} Blown glass can be made much thinner than cast or sagged glass; this significantly reduces not only the amount of raw material involved in its production, but also the time required for the glass to cool evenly and safely after it is shaped.\footnote{Stern 2007, p. 366.} These factors are widely thought to have catalyzed the transformation of glass from a strictly luxury material to an expensive but viable alternative to utilitarian pottery, and the vast majority of Imperial Roman vessel glass is blown. Glassblowing is today the most iconic of glassworking techniques, and with

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.8}
\caption{A disk of glass is sagged into a mold. After Cummings 2001, p. 54.}
\end{figure}
good reason, as it finds no analogy in craft techniques associated with other materials. Cast glass has obvious similarities with cast metal, and other techniques of manipulating hot glass could perhaps be likened to forging, but there is no other material available in the ancient world that can be shaped by breath. The earliest comparable manufacturing technique is that of blow-molding plastic, an innovation of the early 20th century inspired by the principles of glassblowing.

Glass can be free-blown, using a pipe, gravity, and a variety of metal and wooden tools to produce the desired shape; or mold-blown, inserting the blow-pipe with a gather of molten glass into a terracotta mold before inflating the glass. Almost all industrially produced bottle glass today is mold-blown by machines. It was once argued, by the great archaeological glass scholar Donald Harden, that mold-blowing was likely the earlier technique of the two, a direct development from mold-casting, but more recent evidence suggests that free-blowing was invented first, with mold-blown glass following only in the early 1st century A.D.25

The descriptions of these techniques given here assume that the glassworker begins with a supply of ready-made glass in some form, whether broken vessel glass destined for recycling, regular ingots like those found on Bronze Age shipwrecks, or rough chunks of the kind we see in wrecks of the historical period. In classical antiquity, it seems to have been normal for this “raw” glass to be made on a massive scale at a relatively small number of “primary” facilities, and then shaped into useful objects at smaller, more numerous “secondary” workshops. Primary production in the Roman period is not well attested archaeologically, though a few sites are known in the

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Levant and Egypt (see section 4), the most important of these being a complex at Beirut operating in the late 1st century B.C. and early 1st century A.D. Similar, better-preserved facilities dating to the Islamic period, notably those at Bet Eli’ezzer and Tyre, and a famous eight-ton slab of raw glass at Bet She’arim (of uncertain date, between the 4th and 9th centuries A.D.; see figure 2.9), have also been used as comparanda to infer details about the earlier industry.

Primary production took place in enormous rectangular melting tanks; those at Beirut (see figures 2.10 and 2.11) were approximately 4.8 meters by 6.2 meters. The practice of mixing the fuel into the charge, standard when smelting metal in charcoal furnaces, would have resulted in intolerable contamination of the glass and rendered it unusable, so these furnaces must have had separate fire chambers burning timber, much like pottery kilns. Some may have been surrounded by multiple fire chambers. The Beirut furnaces appear to have had a sandstone superstructure, but no remains of walls were found in situ, and they may have been rebuilt after each firing. In addition, the interiors of the tanks seem to have been coated with lime

\[\text{Figure 2.9: The Bet She’arim slab.} \]

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26 Kowatli et al. 2006, pp. 115-117.
27 Kowatli et al. 2006, p. 110.
28 Rehren and Freestone 2015, p. 235.
29 Brill 1988, p. 287.
plaster to insulate the superstructure from the corrosive effects of direct contact with molten glass. This lining, too, would have needed regular replacement. The end result of firing would have been a huge slab of glass like that found at Bet She’arim, which would have had to be “mined” out of the furnace with pickaxes or similar tools, hence the irregular chunks in which raw glass seems to have been shipped and sold. Ethnographic parallels from traditional glassmaking in modern India suggest that the entire process could have taken several weeks.

The Bet She’arim slab seems to have been the result of a serious failure of the production process, probably a mistake in the proportions of the ingredients that caused a critical degree of devitrification. It was therefore never broken up for distribution. Indeed, it was so badly devitrified that it took many years for modern investigators even to recognize it as glass at all.


Figure 2.10: Photograph of the area of the Beirut tank furnace complex excavated by Kowatli. Remains from several phases are visible, including some 1st century A.D. pottery kilns built over the glass furnaces. After Henderson 2013, p. 218.
Figure 2.11: Plan of the phase designated Tank Furnace Complex 2, the best-preserved phase of the site, at Beirut. After Henderson 2013, p. 219.
Furnaces for secondary production, where raw glass was remelted and shaped into finished objects, were much smaller; that of the prolific glass factory at Jalame in Palestine (see figure 2.12), one of the larger examples, was about 2.4 m by 3.6 m.\textsuperscript{32} Like primary furnaces, these were generally built of stone or brick. Several different designs are attested archaeologically, and have been described by Heidi Amrein; these include circular, rectangular, and semi-circular forms.\textsuperscript{33} Generally, glassblowing furnaces in the Roman period seem to have had a “beehive” structure, with multiple stacked chambers; a lower chamber (often dug into the earth) for burning fuel, a middle chamber for heating glass in crucibles, and in some cases possibly an upper chamber for annealing finished objects.\textsuperscript{34} Sometimes multiple forms appear at a single site; Julian Henderson has suggested that the different shapes may reflect different purposes; for instance, some rectangular furnaces may have been free-standing annealing ovens.\textsuperscript{35} It is difficult to be certain, though, since the above-ground portions of furnaces are rarely well preserved.

\textsuperscript{32} G. Weinberg 1988, p. 28.
\textsuperscript{33} Amrein 2001, appendix 1.
\textsuperscript{34} Henderson 2013, p. 229.
\textsuperscript{35} Henderson 2013, p. 229.

Figure 2.12: Reconstruction of the glassblowing furnace at Jalame. Cross-hatching indicates extant material. The lack of any waste glass drippings in the fire chamber indicates that there was a physical barrier between it and the glass. After G. Weinberg 1988, p. 33.
Natural Glasses

Though glass is a synthetic material, whose physical properties bear little in common with those of its crystalline antecedents, a number of natural materials exist that bear important similarities to man-made glasses, and would have influenced the way glass was perceived and used in the ancient world. As previously discussed, the formation of glassy solids requires a combination of extreme heat and the opportunity for relatively rapid cooling. In nature, the main phenomena capable of producing the necessary conditions are volcanic eruptions, meteorite impacts, lightning strikes, and particularly violent fires. Most of these natural glasses are more curiosities than anything else, but obsidian, the best-known volcanic glass, was used extensively in the tool industry by Neolithic and Bronze Age societies. Also, while they are not actually glasses, precious stones are important to the way glass is perceived, since many early civilizations seem to have viewed glass as a sort of artificial gem.

The best-known meteoric glasses are tektites, glasses formed from the superheated terrestrial debris thrown up by major impact events. Tektites are often scattered to distances thousands of kilometers from the impact sites that created them, and occur in a variety of curious spheroid shapes, formed as the molten slag flies through the air and cools. Fulgurites, or “petrified lightning,” are similarly eye-catching; the result of sand that has been struck by lightning (reaching, for a brief instant, temperatures easily capable of vaporizing pure silica), they are common around the world, and typically have branching tubular shapes, normally only a few centimeters long, but

36 Le Bourhis 2014, pp. 27-29.
occasionally much larger. One imagines that these materials were probably known in ancient times; indeed, there is a carved scarab emblem from the tomb of Tutankhamun (see figure 2.13) that seems to have been made from Libyan desert glass, a remnant of a 29 million year old asteroid impact. However, it seems unlikely that their origins would have been understood; Egyptian craftsmen would likely have regarded meteoric glass as a gemstone like any other. Glassy slags can also occasionally form when soil or plants rich in silica phytoliths are burned, and here the physical causes might have been more readily apparent. Conceivably, observing such slags could even have prompted the realization that plant ash could supply some of the chemical components necessary for formation of a silica glass. In general, though, most of these natural glasses are, at best, curiosities. They certainly might have captured ancient imaginations, as the more spectacular examples still capture ours, but the first glass of any great archaeological significance is obsidian.

Figure 2.13: Pectoral in the Egyptian Museum, Cairo, with a scarab jewel carved from yellow-green Libyan desert glass, from the tomb of Tutankhamun, late 14th century B.C. Photograph from http://news.bbc.co.uk/2/hi/science/nature/5196362.stm, accessed 7 August 2015.

38 Henderson 2013, p. 6.  
39 Henderson 2013, p. 6.
Most archaeologists will have at least a passing familiarity with obsidian, the shiny black stone that forms when rhyolitic lava cools very quickly (note that in a geological context “very quickly” can mean over the course of days or weeks). Obsidian is composed mainly of vitreous silica with a highly variable selection of impurities, and differs from other chemically equivalent stones such as granite or rhyolite by virtue of the amorphous molecular structure created by its relatively rapid cooling. The term “volcanic glass” is not merely a poeticism, but an entirely literal description, in materials science terms (though it should be noted that obsidian cannot be worked in the same way as glass, as it lacks the chemical features described below that make glass less viscous than pure silica). As an amorphous solid with no well-defined cleavage patterns, obsidian forms the same type of conchoidal fractures when struck as microcrystalline stones such as flint and chert (as well as man-made glass), resulting in edges that are potentially only a few atoms thick.\textsuperscript{40} Though obsidian blades have inferior durability compared to metal tools and cannot be repaired as effectively, few materials can compete for sharpness, so that obsidian is favored even today for certain precision tools such as surgical scalpels. In some of the pre-Columbian cultures of the Americas, obsidian held sacred status, and was also a common component of weaponry, some of it relatively sophisticated, such as the Aztec \textit{macuahuitl}, a wooden club or sword with rows of inset obsidian blades.\textsuperscript{41} In the Mediterranean, the obsidian deposits of Melos are known to have been exploited since at least the Neolithic, thanks to the presence at sites around the Aegean of obsidian flakes that can confidently be sourced to Melos by their trace element

\textsuperscript{40} Henderson 2013, pp. 2-4.
\textsuperscript{41} Saunders 2001.
signatures.\textsuperscript{42} The material’s wide distribution from its Cycladic source speaks to its great value in a prehistoric society, particularly one with limited or nonexistent metallurgical technology. Likewise in the Near East, where obsidian sources are similarly difficult to come by, obsidian derived from central Anatolia can be found in quantity as far away as southern Israel during the Chalcolithic period.\textsuperscript{43}

Obsidian did not hold so lofty a position in the classical Mediterranean, though it was certainly known and used. It has been argued that the manufacture of obsidian blades continued in both Greece and Italy until at least the 5\textsuperscript{th} century B.C., and indeed perhaps throughout history until the industrial revolution.\textsuperscript{44} However, its importance was unquestionably much reduced compared to earlier periods and it was primarily used as a semi-precious stone, regularly occurring as an inlay in statuary (for instance, to represent the pupils of eyes). Pliny the Elder describes a substance called \textit{obsiana}, almost undoubtedly our obsidian (\textit{HN} 36.67), which he classifies \textit{in genere vitri}, presumably because of the physical similarities between glass and obsidian. He also claims to have seen obsidian \textit{imagines} of the Emperor Augustus, who himself is said to have placed four obsidian elephants in the Temple of Concord in Rome, but this account is questionable. The sheer difficulty of carving obsidian, which like most glassy solids is extremely prone to shattering, as well as the rarity of pieces large enough for more than a figurine, makes it seem far more likely that what Pliny saw was a finely polished basalt, black marble, or other similar stone. Pliny recommends obsidian shards as a means of identifying counterfeit gemstones, saying that obsidian

\textsuperscript{42} Renfrew \textit{et al.} 1965 is one of the earliest studies; Frahm \textit{et al.} 2014 begin with a good overview of work since then. Famously, Melian obsidian was brought to Franchthi Cave, in the Argolid, as early as the Mesolithic; see Renfrew and Aspinall 1990.

\textsuperscript{43} Yellin \textit{et al.} 1996.

\textsuperscript{44} Runnels 1982, p. 365.
will scratch artificial gems made by “dyeing” rock crystal, but not real ones (HN 37.76); it seems likely that some of the counterfeits to which he refers were made of glass.

In archaeometry, obsidian is perhaps best known for providing a method of absolute dating, albeit a somewhat haphazard one, based on the gradual hydration of the material. Obsidian hydration dating is most often used in North American and Pacific archaeology, but its potential has been investigated in most regions where obsidian tools are common. A freshly flaked obsidian surface should in theory be anhydrous, and will slowly develop a hydrated “rind” from exposure to moisture as water diffuses inward, incorporating −OH groups into the silica matrix of the glass. Assuming a constant rate of hydration, it is possible to determine the age of the surface, and hence the time since the obsidian was worked, by measuring the thickness of the hydrated layer. In practice, the rate of hydration fluctuates with temperature, humidity and the precise composition of the sample; it is not even possible in all cases to assume negligible initial hydration. Temperature and humidity averages over time can be estimated, and tend to be more stable for deeply buried samples. If the geological source of the obsidian can be securely identified it is also possible to investigate the chemistry of that source and perform induced hydration experiments to determine how the sample’s hydration rate might have fluctuated over time as environmental conditions changed. Efforts of this kind in Bronze Age Aegean archaeology have been promising, as the ubiquitous Melian obsidian seems to have a particularly homogeneous composition, even between the deposit’s two major flows. Nonetheless, if there is any uncertainty at all about a sample’s depositional history,

and in particular about how long it remained unburied (since buried samples tend to be exposed to significantly more water and lower temperatures than surface ones), it is probably wisest to regard obsidian hydration dates as relative rather than absolute, and they will rarely be the most secure figures available for any given context.

While they are not actually glasses themselves, it is here worth mentioning some other natural antecedents that may have inspired glassworkers through their own properties: precious stones. In the Bronze Age, civilizations that used glass do not seem to have had words for it, as Latin does; they instead seem to have regarded glasses primarily as artificial versions of the gemstones that shared their brilliant colors (and, in some cases, translucency). Hieroglyphic Egyptian, for instance, combines the names of precious stones with a determinative sign for fire to indicate something like “molten stone.” Similarly, glass is attested in Linear B as $ku$-$wa$-$no$ (classical Greek κυανός, literally an adjective meaning dark blue, presumably because most of the glass known to the Mycenaeans was, in fact, dark blue cobalt glass), the same word used for lapis lazuli. From terms like this it seems clear that glass was for a long time not generally regarded as being fundamentally different from the gems it resembled. Since gemstones in the ancient world were often considered to possess magical powers, the value of being able to create artificial ones should be obvious.

By the Roman period, of course, glassmaking appears to have been greatly demystified, to the extent that non-professionals like Pliny are able to give a reasonably accurate factual account of how glass is made from sand (see section 3).

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48 Stern 2007, p. 388.
49 Henderson 2013, p. 7.
Vessels carved from precious stones are exceptionally rare in archaeology, though a variety of literary references should lead us to expect that more did exist, and these may have been an important influence on glassworkers. The most important stone here is probably rock crystal – colorless, transparent quartz. Rock crystal is cheap today, but Pliny regarded it as the most valuable material of all those *extra tellurem*, that is, those that can be found on the earth’s surface (*HN 37.78*). Michael Vickers has argued that the relationship of cut glass to rock crystal (and, indeed, other precious stones from which vessels might have been carved) in classical antiquity was essentially the same as that of bronze to gold, pewter to silver, or pottery to metals: a cheaper alternative that could produce a good imitation. Some of his comparanda in rock crystal do not actually exist, but are inferred from gold and silver skeuomorphs or literary references, and at times he seems motivated by hostility towards the field of glass studies itself, but the basic point is sound; the prolific Imperial Roman tradition of facet-cut glass (see figure 2.14 for an example), much of which is colorless, likely owes a great deal to crystal carving.

Figure 2.14: Early 2nd century A.D. Roman facet-cut glass bowl in the British Museum, of the kind Vickers attributes to imitation of rock crystal originals, from a grave at Leuna, Germany. After Harden 1987, p. 196.

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50 Vickers 1996.  
Composition and Chemistry of Glass

Hellenistic, Roman, and Byzantine glass is normally soda-lime glass, and bears a closer resemblance to commercially-made modern glassware than to most other historical glass compositions. Its principal chemical components are silica (silicon dioxide, SiO$_2$, the major constituent of quartz and most sands), which makes up most of the structure of the glass, soda (sodium oxide, Na$_2$O), which renders the silica workable (see below), and lime (calcium oxide, CaO), which helps to compensate for the inferior chemical resistance of soda glass compared to pure silica (see below). In the Roman period, as today, both of the later two ingredients were likely added in the form of their respective carbonates (CaCO$_3$, Na$_2$CO$_3$), which undergo thermal decomposition to the oxides and carbon dioxide (CO$_2$) upon exposure to high temperatures such as those of a kiln.

Much work on characterizing Roman glass in the last few decades has centered on determining the probable sources of each of these three compounds though stable isotope analyses and trace element characterization (see section 4). Silica can be found in abundance on any beach, and it is with this component that most trace heavy metals enter a typical glass melt, along with the minor components iron (II) oxide (FeO) and alumina (aluminum oxide, Al$_2$O$_3$). Calcium carbonate is the principal component of limestone (in the form of calcite) and of seashells (in the form of aragonite), both readily available in the ancient Mediterranean, though it seems likely that Roman glassmakers added shell as a component of beach sand, not as a separate ingredient.\textsuperscript{52} Sodium carbonate is harder to come by and was likely sourced from the

\textsuperscript{52} Freestone \textit{et al.} 2003; Brill 1988, pp. 265-269.
Dry lake beds of Egypt, most famously the lakes of the Wadi Natrun area, which derives its name from the common term for this compound, “natron.”

Pure crystalline silica has a melting point of roughly 1700 °C, almost certainly beyond the reach of ancient pyrotechnology. Moreover, liquid silica is extremely viscous even at temperatures quite close to its melting point, and is all but unworkable. The addition of soda to silica lowers the melting point to a more achievable 1100-1300 °C (depending on the exact quantity added); in such a mixture of solids, compounds with lower melting points will melt readily and then dissolve those with higher melting points, so that the entire mixture becomes liquid at a lower temperature than its components normally would. It also allows extra metal and oxygen atoms to infiltrate the silica lattice in the formation of the glass, further disrupting the

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53 In geochemistry, the word “natron” refers strictly to the decahydrate form of sodium carbonate (Na₂CO₃·10H₂O). However, the *nitrum* used by ancient glassmakers would actually have consisted of a mixture of several sodium salts that varied in their precise composition with the seasons and from one lake bed to another (Shortland *et al.* 2006, 525-526); the principal component of these mixtures is likely to have been not “natron” in the strict sense but trona, sodium carbonate-bicarbonate dihydrate (Na₃CO₃·HCO₃·2H₂O). Archaeology simply refers to all of it as “natron,” reflecting ancient practice.

54 Firing temperatures for Roman (and indeed Greek) pottery determined by experimental archaeology rarely exceed 1100 °C by a significant margin. Iron smelting may have occasioned higher temperatures, but probably not much over the 1150 °C required to easily drain off most typical impurities (Healy 1978, p. 183).

55 Le Bourhis 2014, p. 213.
regularity of its crystal structure and widening any gaps in it (see figure 2.15). This lowers the temperatures required to soften and eventually melt the glass when it is reheated for working, and reduces its viscosity. Silica adulterated in this way thus remains fluid enough to be workable at much lower temperatures, 1000 °C being typical for Roman glass.56 Natron is not the only substance that can be added to silica to produce this effect – oxides of a variety of alkali and alkaline earth metals can be used; compounds added to glass for this purpose are known generically as fluxes. However, sodium oxide is by far the most common flux in Roman glass, and is also used extensively in modern glass production.

While common today, the use of a mineral sodium-based flux is, in fact, a relatively unusual phenomenon in glass history. Although natron dominates archaeological glass assemblages in the Mediterranean for most of the first millennia B.C. and A.D., glassmaking before and after this period was mainly reliant on the use of ash from halophytic plants (plants that grow well in high-salinity water), most famously species of the genera Salsola (the saltworts) and Salicornia (the glassworts).57 Such glasses are easily distinguishable from natron-based glasses because plant ash is much less pure in composition than natron; in particular, high levels of magnesium and potassium are common for ash glasses. This is the only kind of glass known in significant quantities from the Mediterranean Bronze Age, and also dominates the ancient Persian and subsequent Islamic traditions. Mediaeval European glassmaking instead favors wood ash, which produces a glass that is similar to other ash glasses but much lower in sodium, with potash (potassium oxide, K₂O) taking the place of

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56 Brill 1988, p. 279.
57 Shortland et al. 2006, p. 522; Freestone 2006, p. 204.
soda in governing the physical properties of the glass.\textsuperscript{58} Calcium in plant ash glasses would have been supplied by the ash itself, and its addition in the form of either calciferous sand or a separate ingredient such as limestone would not have been necessary; accordingly, many ash glass industries seem to have used ground quartz pebbles or other high-purity silica sources rather than sand.\textsuperscript{59} Ancient Indian glass seems to use a potassium-rich mineral flux that has yet to be conclusively identified, while Han China produces a unique glass type high in lead and barium, whose precise nature is even more enigmatic.\textsuperscript{60} There is also some evidence for the use, in Iron Age Italy, of a flux low in both sodium and magnesium, but high in potassium, calcium and phosphorus, which may have been bone ash, though archaeologically this evidence is questionable at best.\textsuperscript{61}

Man-made glasses in archaeological contexts share many of the resilient features of pottery, which is famous in archaeology for its “indestructibility,” but unlike pottery can be gradually corroded by water. Sodium or potassium can be leached out of the silica network by water or acids, in the process also incorporating hydrogen ions into the glass in their place and forming a silica gel layer (this is the process that obsidian hydration dating seeks to measure). This process increases the alkalinity of the surrounding solution; if the pH reaches 9, it can begin to degrade the silica network

\textsuperscript{58} Shortland \textit{et al.} 2006, p. 523. The basic distinction between halophytic and terrestrial plant ash could be only the beginning of what chemical characterisation can tell us – it should be possible to link ratios of minor or trace elements in glass composition to the ashes of specific plant species (Henderson 2013, 36-42). Research in this area is currently underdeveloped, and its relevance to this review somewhat tangential as Roman glass is almost invariably made with a mineral sodium flux, but the potential for further development, perhaps leading to insights into locations of manufacture and resource exploitation, is nonetheless extremely exciting.

\textsuperscript{59} Tite \textit{et al.} 2002, p. 588.

\textsuperscript{60} Rehren and Freestone 2015, p. 234.

\textsuperscript{61} Towle and Henderson 2007, pp. 53-55.
itself and thus destroy the physical structure of the glass, through the reaction of hydroxide (OH⁻) ions with the Si-O bonds of the glass.62 Because the second of these processes is often dependent on the first, and is also far more damaging, glass – somewhat counterintuitively – actually degrades more quickly in still water or an enclosed humid atmosphere, where the alkalinity of the solution is allowed to build up over time, than in flowing or open water such as a river or the ocean.63 Shipwrecks therefore tend to be good sources of archaeological glass. Experiments have shown that potash glasses with particularly unfavorable compositions can exhibit clearly visible signs of a variety of corrosion processes within a year, if buried in soil.64 Historical glass compositions meant for practical use are, for obvious reasons, far more resilient, though it is rare to find archaeological glass that has suffered no corrosion at all.

Naturally, the choice and quantity of fluxing agents used in the glass can have significant effects on its resistance to corrosion. Pure vitreous silica, for all its egregious flaws as a craft material, is largely impervious to water damage; a flux is necessary for the glass to be workable, but also necessitates careful balancing of the different components in order to achieve acceptable chemical resistance. The impact of the many possible fluxing compounds and other components of various glass types on corrosion processes is, needless to say, an extremely complex subject and the object of a great deal of study, as much by the modern glass industry as by archaeologists and conservators; however, certain general principles can be described

62 Le Bourhis 2014, pp. 82-83.
63 Frank 1982, p. 12.
64 Römich and Lopez 2002.
here. For instance, glasses made with potassium-based fluxes rather than sodium-based ones, such as most Mediaeval European glasses, tend to be significantly more vulnerable to corrosion by this mechanism than Roman soda glass, possibly due to the lower charge density of potassium ions compared to sodium ions and the consequently weaker bonds they form with oxygen.

Other ingredients seem to be used in ancient glass to increase its resistance to corrosion, most notably compounds of alkaline earth metals such as calcium and magnesium. Oddly, there is some evidence that calcium actually has the opposite effect in potash glasses, apparently accelerating corrosion rather than inhibiting it as it does in soda and mixed alkali glasses – just one example of the complexities involved in the interactions of multiple ingredients. In many cases, calcium oxide could have been supplied simply by choosing a calciferous sand as the silica source, though there may be some indications (see section 4) that the calcium in Roman glass was sometimes derived from another ingredient added separately, such as crushed seashells. Early Iron Age soda glasses regularly lack such stabilizing components, except for those added incidentally as colorants; as a result, preservation of glasses from this period is generally poor unless conditions are exceptionally favorable.

The final ingredient to be discussed is an optional one: color. A wide selection of colorants was available to Roman glassmakers, ranging from the commonplace (such as blue-green copper compounds), many of which had been in use since at least the

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65 Melcher and Schreider 2013, p. 621.
68 Melcher and Schreider 2013, p. 623.
time of the Egyptian New Kingdom, to the surprisingly exotic (including, on at least one occasion, uranium dioxide, UO$_2$, which imparts to glass a lime green color that was popular around the world in the late 19th century A.D.).\textsuperscript{70} In Bronze Age production, colorants were probably added during the creation of raw glass ingots.\textsuperscript{71} In the Roman period, by contrast, it may have been more common to mix colored glass at the secondary level. All of the colorants commonly used are probably derived from mineral sources, and most owe their hues to various oxides of the transition metals, atoms of which can substitute for silicon in the glass lattice in a similar way to the alkali and alkaline earth metals discussed above. Many transition metals can interconvert easily between two or more differently-colored oxidation states by accepting or donating oxygen, a process which can be controlled by manipulating the atmosphere of the furnace or kiln. Copper, for example, can yield the blue-green of copper (II) oxide (or cupric oxide, CuO) in an oxidizing atmosphere, or the red of copper (I) oxide (cuprous oxide, Cu$_2$O) in a reducing atmosphere (the same principle underlies the use of the black iron-based pigment that characterizes Attic black figure pottery).\textsuperscript{72} Both forms of copper are common in glass throughout antiquity, particularly during the Bronze Age.

Most ancient glass is naturally a faint blue-green due to the presence of small amounts of iron compounds in the sand used to make it, incorporated into the glass as iron (II) oxide (ferrous oxide, FeO).\textsuperscript{73} One may readily observe a similar hue by looking at a

\textsuperscript{70} Caley 1948. The veracity of this result has been disputed by Freestone 1998.
\textsuperscript{71} Rehren and Freestone 2015, p. 236.
\textsuperscript{72} Fiori \textit{et al.} 2004, p. 74.
\textsuperscript{73} It is for this reason important to distinguish between \textit{uncolored} ancient glass, which has this blue-green hue as a result of impurities in the raw materials rather than any specific extra ingredient, and \textit{colorless} glass, which is colorless due to the action of deliberate additives such as manganese (see below).
sheet of modern window glass edge-on, and the deliberate addition of iron can strengthen it. Melting the raw ingredients in a furnace with a reducing atmosphere will cause those same impurities to produce a range of colors from olive green to golden yellow which are also common in Roman glass, though less so than the natural blue-green – these result from the creation of a bright amber-colored ferri-sulfide complex (FeS\(^+\)), in combination with the existing blue of the iron.\(^{74}\) The color of this complex is extremely intense, and so only tiny amounts of sulfur need be present in the glass mixture to produce it. Perhaps the most common added color in ancient glass prior to the Roman period is the deep blue of cobalt (II) oxide (CoO). Cobalt can in fact be made to produce a vivid pink as well when pushed into a higher oxidation state, but ancient glassmakers do not appear to have exploited this possibility.\(^{75}\) Crystalline inclusions of calcium antimonate (Ca\(_2\)Sb\(_2\)O\(_7\)) yield opaque white; lead antimonate (Pb\(_2\)Sb\(_2\)O\(_7\)) crystals likewise produce a bright opaque yellow.\(^{76}\) Other opaque colors can readily be obtained by mixing a translucent glass and a second glass made with either of these two opacifiers.

One of the most important colorants in the Roman period is manganese. Manganese (III) oxide (Mn\(_2\)O\(_3\)) in large amounts imparts an unmistakable vivid purple color, which is fairly common in Roman glass, though it is more often used in smaller quantities, where it can actually remove the natural greenish tint of most ancient glass and produce colorless wares by oxidizing the iron (II) impurities to almost-colorless iron (III).\(^{77}\) The color of any remaining iron (II) is offset by the faint yellow of manganese (II) oxide (MnO) and the pink of unreacted manganese (III), resulting in a

\(^{74}\) Brill 1988, pp. 288-294; Fiori et al. 2004, p. 76.
\(^{75}\) Fiori et al. 2004, p. 73.
\(^{76}\) e.g. Arletti et al. 2006, p. 178.
\(^{77}\) Fiori et al. 2004, pp. 76-77.
very faint, dull grey that we perceive as “water white.”\textsuperscript{78} Manganese is used to a similar effect in a great deal of early modern glass. Colorless vessel glass is attested archaeologically in the Near East from at least the 8\textsuperscript{th} century B.C. \textsuperscript{79} The decolorizing agent in these earlier examples is antimony, which works by a similar mechanism. Manganese likely takes over as the standard at some point in the 2\textsuperscript{nd} or 1\textsuperscript{st} century B.C., though the two are sometimes used together in the Imperial period.\textsuperscript{80} Colorless glass is far from unheard of in the Hellenistic period; indeed many fine examples exist. Its popularity during the Imperial period, however, is unprecedented. Beginning from the end of the Julio-Claudian period, fine glass tablewares are almost always decolorized, while less expensive wares also adopt a more subdued palette compared to the often spectacularly colored glassware favored in Italy at the end of the Republican period.\textsuperscript{81}

\textbf{Conclusion}

Important properties of glass to be kept in mind in reading subsequent chapters of this review include the following. First, glass is a synthetic material derived from at least two naturally occurring substances, which in the Roman period are normally sand and natron salts. These react under extreme heat to form an irregular network of covalently bonded atoms, with the SiO$_4$ tetrahedron as the base unit, but with no long-range order or symmetry in its molecular structure, and other metal atoms infiltrating the network essentially at random. Although the physical and chemical properties of glass are sensitive to the ingredients used, and their proportions, several

\begin{flushleft}
\textsuperscript{78} Brill 1988, p. 277.  \\
\textsuperscript{79} Von Saldern 1959.  \\
\textsuperscript{80} Arletti \textit{et al.} 2006, p. 182, Henderson 2013, p. 246.  \\
\textsuperscript{81} Grose 1991, p. 14.
\end{flushleft}
 compositional ranges are viable. Second, the properties of glass that make it unique from a craft perspective, including its transparency, its pliable consistency at high temperature, the mechanics of the annealing process, and the ease with which it can adopt a wide variety of bright colors, are all the result of its molecular structure. Third, the creation of raw glass from its naturally occurring antecedents should be distinguished from the creation of glass objects from raw glass, as the two processes are not always closely associated in time or space; indeed, in the Roman period, they are usually separate. Fourth and finally, the unusual properties of glass make it difficult to classify in relation to typical categories of materials known in the ancient world; it has traits of pottery (hardness, brittleness, generally good chemical resistance), metal (can be worked while hot and fluid), and gemstones (bright colors, reflective surface, often translucent). These traits govern the uses to which glass can be put in the ancient world, to be discussed in section 3, and they also often have significant impacts on what useful information we can infer from its chemical composition, to be discussed in section 4.
Section 3: The History of Glassworking and Roman Sources on Glass

Introduction

Glassworking as we know it today owes a great deal to the invention of blown glass, an innovation of Syro-Palestinian artisans in the final days of the Hellenistic period, spread and popularized by the Roman Empire. The history of glassworking goes back much further than this, however. Vessel glass was made in Egypt and Mesopotamia during the Late Bronze Age, and the materials from which it developed, most notably faience, were already part of an artistic tradition of great antiquity even then. Greek and Roman glass artisans were the inheritors of, and innovators within, an artistic tradition of great antiquity, of which this chapter will attempt to provide an overview, with particular attention to its material and technical aspects. In large part, this chapter is intended to provide background and context. In archaeometry, divisions of the field are commonly arranged along lines of material, not region or period. It is therefore important for classicists with an interest in glass studies to pay at least cursory attention to developments in the study of Bronze Age and early Mediaeval glass. Being aware of trends in these fields can help us to appreciate what makes the Roman glass industry a particularly interesting phenomenon, by contrasting it with what came before and after. This chapter also includes, again with the aim of providing context, some discussion of the way glass is presented in literary sources of the Roman period, principally the *Natural History* of Pliny the Elder. Appreciating the cultural context of Roman glass might seem like a strange direction to prioritize in an archaeometric study, and for chemists actually performing analyses, it is certainly a secondary concern. However, for archaeologists trying to convert analytical data,
relating mainly to the progress of technology, into useful statements about cultural
change, it can be helpful to know what the Romans themselves (or, at least, certain
educated Romans) considered to be the most important aspects of the technology, and
the sources of its value.

**Man-Made Precursors to Glass**

The oldest known man-made “glasses” are glazed stones and faience (sometimes
called “glass paste”), both of which were probably first produced in Mesopotamia and
Egypt at the end of the 5th millennium B.C. In form, these artifacts have little in
common with later vessel glass; most are small beads and other components of
jewelry. Glazed stones are carved pieces of stone (most commonly steatite or
“soapstone,” a soft talc-rich schist) with an artificial glassy coating that gives them an
attractive color (most commonly the blue-green of copper compounds) and luster.
Faience is a similar glassy coating around a core of powdered quartz, which is
moistened to create a moldable paste. Bronze Age artisans could manipulate this
paste with a great deal of skill, and it could even be thrown on a potter’s wheel to
create vases. 82 Many techniques for shaping and decorating glass involve
manipulating pliable or liquid hot glass (see section 2), but glazed stones and faience
are only shaped before firing, while the materials are cold, and thus have more in
common with clay than glass from a technological standpoint. The core is carved or
molded, then either coated with a glazing mixture (direct application) or submerged in
it (cementation); the piece is then fired at about 900 °C, and any excess glazing

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82 Panagiotaki 1997, p. 303.
mixture is crumbled away.\textsuperscript{83} For faience, there is a third option; combining the glazing mixture with the core material, then leaving the shaped piece to dry before firing, so that the salts of the flux form a crust on the surface (efflorescence). The practical and aesthetic results are similar regardless of the glazing method used. The fundamental differences in production technique between these early vitreous materials and true vessel glass may explain why it took so long for vessel glass to appear in Egypt and the Near East after the invention of glazed stone and faience; hot-forming requires artisans to think about the material in an entirely different way.\textsuperscript{84}

Steatite glazes and faience are similar in chemical composition to early copper-blue glasses, containing silica, alkali derived from plant ash, and copper compounds. It is likely that the silica was supplied entirely by the material of the core (stone or quartz dust), thus creating a glassy layer of roughly uniform thickness at the interface between the core and the glazing mixture.\textsuperscript{85} The glazing mixture would have consisted of an alkali flux (plant ash or natron) together with a copper source (usually filings of scrap bronze, judging by the associated trace metals, but possibly powdered malachite in some early cases). Interestingly, examples of the very earliest Egyptian glazes, from the 5\textsuperscript{th} millennium Badarian culture, seem to have been made using natron as the alkali flux, not plant ash as is the case for the overwhelming majority of vitreous materials throughout the eastern Mediterranean during the Bronze Age.\textsuperscript{86} The reasons for the apparent abandonment of natron in subsequent periods are unclear, though it is possible that a mixture of natron and plant ash was used in some

\textsuperscript{83} Tite and Bimson 1989, p. 87.
\textsuperscript{84} Tite \textit{et al.} 2002, p. 588.
\textsuperscript{85} Tite and Bimson 1989, p. 94; Tite \textit{et al.} 2002, p. 587.
\textsuperscript{86} Tite and Bimson 1989, p. 89.
Although copper blue remains the most important pigment in faience throughout the eastern Mediterranean until the end of the Bronze Age, many other colors are introduced as well, particularly after the invention of vessel glass. Polychrome faience figurines, plaques, and jewelry, made using inlay and marbling techniques, are also known from the Middle and Late Bronze Age in both Egypt and Minoan Crete.

A related material is the synthetic pigment known as Egyptian Blue. This is a staple of Egyptian art, and remains the most commonly used blue pigment in Mediterranean wall painting throughout antiquity, until the loss of the “recipe” necessitated a switch to more expensive natural pigments, such as azurite, at some point in the early Mediaeval period. Egyptian Blue is not a glass, but rather a complex particulate mixture of glasses and crystalline copper silicates, the most important one being equivalent in structure and composition to the naturally-occurring mineral cuprorivaite (CaCuSi₄O₁₀). Like early copper-blue glass, Egyptian Blue was made by firing a silica source with a copper source in a furnace or kiln; unlike glass, the firing mixture for Egyptian Blue contains no alkali flux. As a result, it does not form a vitreous mass when fired, but remains sandy in texture. Despite these differences, Egyptian Blue forms a part of the same series of technological developments as glass, including the idea that the properties of sand could be altered by extreme heat, and the

88 Tite et al. 2008, pp. 43-45, pp. 54-55.
89 Orna et al. 1980. Mediaeval attempts to synthesize Egyptian Blue using the instructions given by Vitruvius (De Arch. 7.11) seem to have ended in failure, likely because he does not adequately specify the required type and quality of sand, which must serve as a source of calcium as well as silica (Chiari and Scott 2004).
90 El Goresy 2000, p. 58.
use of metallic copper or bronze to produce a light blue color. As such, it is regularly discussed alongside glasses and faience in studies of Bronze Age technology.  

How exactly these first basic vitreous materials were discovered remains within the realm of conjecture. Based on the overwhelming dominance of copper blue over other colors, particularly in the earliest periods of their manufacture, it seems likely that they were first developed as a result of chance observations made by Neolithic copper smelters. Sandstone furnace walls would provide a source of silica, while the ash left behind by certain plants used as fuel could have contributed the necessary sodium flux. An alternative suggestion made by Anita Engle envisions similar chance observations resulting instead from the offering of burnt sacrifices on a sandstone altar, perhaps in the presence of copper or malachite, both of which have known ritual functions in the prehistoric Near East. Such an origin would certainly dovetail pleasingly with the value and possible sanctity of many faience (and later true glass) objects in the Bronze Age. However, those traits are not especially in want of an explanation, and can sensibly be attributed to the pleasing visual properties of colored glasses, and their resemblance to a variety of gemstones, themselves often considered sacred or magical materials.

The Glass Industry in the Bronze Age

The first true glass, probably Mesopotamian in origin, is mid-3rd millennium B.C. in date, and, like faience, was mainly used in small items such as beads until the

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91 e.g. Tite and Shortland 2008.
93 Engle 1978, p. 16.
appearance of core-formed glass vessels c. 1500 B.C. From there, glass artifacts quickly became common in Egypt as well, probably in the aftermath of Tuthmosis III’s successful Mesopotamian campaigns in the 15th century B.C., and the period of close relations between Egypt and Mesopotamia during the reign of Tuthmosis IV. “International” trade in glass is attested by the cargoes of shipwrecks like that at Uluburun, which contained over a hundred raw glass ingots, suitable for reheating for use by artisans. Glass vessels and jewelry are also known from Mycenaean Greek sites, though the extent of the Mycenaeans’ own technical capabilities with respect to glass is unclear. Northern Italy seems to have had an independent primary glass industry as well, though unlike its eastern counterparts this does not seem to have persisted far into the Iron Age.

As it would be in classical antiquity, Egypt was part of the core region of the Bronze Age glass industry, with several workshops documented by archaeologists. The earliest currently known to have made glass vessels is that at the palace of the 18th dynasty pharaoh Amenhotep III (early to mid-14th century B.C.) at Malkata. Perhaps the most prolific, and easily the best-studied

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94 Henderson 2013, p. 8.
96 Yalçın et al. 2005, pp. 68-71. These are not the oxhide shape that will be familiar to Bronze Age archaeologists as the standard form of copper ingots, but circular “cakes” of glass.
97 Towle 2002, pp. 327-351.
glassworking site of the Mediterranean Bronze Age following Paul Nicholson’s excavation in the 1990s, is at Amarna, the royal capital of Amenhotep’s successor, the heretical pharaoh Akhenaten (mid-14th century B.C.). Glassworkers at Amarna used plant ash glasses in a variety of colors, predominantly copper blue and cobalt blue, though rods in several other colors are present, and would likely have been used in the production of elaborate polychrome core-formed vessels in the “zig-zag” decorative style described in section 2 (see figure 3.1).

In addition to core-forming, certain images in Egyptian art were at one time widely thought to depict glassblowing as far back as the 19th century B.C. (see figure 3.2). This flies in the face of all archaeological evidence for glass production in Egypt, and serious glass historians now believe that these images actually show metalworkers using reed pipes to start and encourage fires.

It has been argued that the New Kingdom produced some raw glass itself in addition to worked vessels, as the cobalt used in Egyptian cobalt blue glass can confidently be tied to the Kharga Oasis in the Western Desert by trace element analysis, while Mesopotamian cobalt blue glass has a different source, probably in Iran. It is

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100 Jackson and Nicholson 2007, p. 106.
possible that this reflects the use of Egyptian cobalt-bearing materials to color a pre-made uncolored raw glass imported from elsewhere. However, considering the rarity of uncolored glass in the Bronze Age, it seems more likely that colorants were added during primary production; it has been suggested that each primary center specialized in a single color produced using a single recipe.\textsuperscript{104} Royal communications of the period suggest that domestic supplies of raw glass would have been augmented by imports from Levantine allies and vassals, which were presumably worked into finished pieces in the Amarna workshop and similar sites.\textsuperscript{105} Furthermore, royal letters rarely display interest in any specific commodities provided by Levantine kings other than bulk quantities of this sparkling “stone,” which seems to have been an important export for those states.

In the Aegean, the earliest evidence for the manipulation of true glass comes from LM IB (16\textsuperscript{th} or early 15\textsuperscript{th} century B.C.) Knossos, where a workshop on the side of the Royal Road was likely responsible for a variety of glass decorative elements, including plaques, inlays, and pommel jewels, as well as similar objects.

\textsuperscript{104} Rehren and Freestone 2015, p. 236.
\textsuperscript{105} Engle 1978, p. 47.
executed in faience.\textsuperscript{106} Minoan artists by this point already had a long history of skillful faience work, probably the most famous examples being the “snake goddess” figurines from the LM IA Temple Repositories. This prior expertise with vitreous materials doubtless served them well, though there is at present no evidence that the Minoans ever made raw glass from scratch themselves, or made glass vessels. On the mainland, the work of Marina Panagiotaki \textit{et al.} on material from Heinrich Schliemann’s excavation at Tiryns has demonstrated the existence of workshops that produced cast glass beads and inlays (see figure 3.3 for examples), in both copper blue and cobalt blue.\textsuperscript{107} However, there is again no archaeological evidence for the production of glass vessels, nor for the manufacture of raw glass; they conclude that the workshop’s activities were probably sustained by a brisk trade in glass ingots, like those found at Uluburun. Chemical data they obtained supports this idea, as the Tirynthian samples are similar in composition to both Egyptian glasses and the Uluburun ingots. It is worth bearing in mind, however, that recent developments in the analysis of Roman glass give us reason to doubt that straightforward analysis of major element composition is the best way of ascertaining locations of manufacture in glass studies, and to my knowledge these ideas have not yet been extensively applied to the Bronze Age glass industry (see section 4).

A completely independent glassmaking tradition appears to have existed in western Europe during the Bronze Age; its northern Italian branch was investigated in some depth by Andy Towle in his PhD thesis at the University of Nottingham. The most prominent site for this region is the Proto-Villanovan town of Frattesina in the Po Valley, which produced glass with a “mixed alkali” composition, high in both sodium

\textsuperscript{106} Panagiotaki 1997, pp. 307-308.  
\textsuperscript{107} Panagiotaki \textit{et al.} 2003.
and potassium, that is unknown outside of Bronze Age Europe.\textsuperscript{108} This composition probably suggests that it was made using plant ash, like the Bronze Age glasses we know from Egypt and the Near East, but derived from different species, and reflective of the regional ecology. Like Minoan and Mycenaean glassworkers, the artisans of the western European Bronze Age do not appear to have made glass vessels, only beads, jewelry, and other decorative items. However, they did make use of a variety of colors (copper blue and cobalt blue being, again, the most common), and also produced objects with polychrome trail decoration similar to that seen on eastern core-formed vessels (see figure 3.4).\textsuperscript{109} The mixed alkali technology does not appear to have persisted into the historical period, and the Etruscan glass industry seems to have been driven entirely by imported Levantine raw glass, although the existence of uniquely Etruscan core-formed vessel styles does attest to the presence of skilled secondary glassworkers.\textsuperscript{110}

Glass in the Bronze Age is regularly linked with metalworking, and before moving on it is worth dwelling briefly on the implications of this. Julian Henderson stresses the early adoption and great prominence of copper to suggest such a connection.\textsuperscript{111} Other mineral colorants adopted in the first days of the production of vessel glass suggest similar links; lead antimonate yellow was probably derived, as it would still be in

\textsuperscript{108} Towle 2002, pp. 327-351.
\textsuperscript{110} Towle and Henderson 2007.
\textsuperscript{111} Henderson 2013, p. 7.
Roman times, from litharge (a form of lead oxide that is regularly associated with antimony), a by-product of the cupellation of silver from argentiferous galena.\textsuperscript{112} Moreover, the high-temperature core-forming processes used by the makers of the first vessel glass would certainly have benefited from the existing equipment and expertise of metalworkers, and glass and metal regularly occur together in Bronze Age jewelry, suggesting collaboration.\textsuperscript{113} In some cases, the glassmakers and the metallurgists may even have been the same people. Much is made of the seemingly “magical” nature of the transformative processes involved in metalworking and the prestige, even mystique, with which this would have imbued its first practitioners in the late Neolithic and the Bronze Age.\textsuperscript{114} The first makers of faience and glass would likely have enjoyed a similar status; after all, these were people who, to put it poetically, created gemstones from fire and sand.

**Glass in the 1\textsuperscript{st} Millennium B.C.**

Glass is extremely rare in the centuries following the Bronze Age collapse, as one might expect of a luxury product in a period of instability, and not much work has been done on what little there is. The key point of interest for this period is how much continuity there was between the Bronze Age glass industry and that of the early Iron Age, and the limited evidence makes this an open question for now.\textsuperscript{115} However, this period did notably see the introduction of new glass types with different properties: natron glasses. The earliest firm evidence for the use of natron as the sole flux in vessel glass occurs, unsurprisingly, in Egypt, in the early 10\textsuperscript{th} century.

\begin{itemize}
\item \textsuperscript{112} Mass \textit{et al.} 2002, p. 71.
\item \textsuperscript{113} Peltenburg 1987, p. 20.
\item \textsuperscript{114} \textit{e.g.} Budd and Taylor 1995.
\item \textsuperscript{115} Reade \textit{et al.} 2003, p. 23.
\end{itemize}
B.C. tomb of the noblewoman Neskhons. In 9th century B.C. Nimrud, the newly established capital of the Neo-Assyrian Empire, natron glass coexisted with the older ash-based recipes, and natron is associated with cobalt colorants probably derived from outside of Egypt. The very low calcium content of these glasses suggests that they were made using very pure sources of both sodium (natron) and silicon (likely crushed quartz), and because of this the chemical resistance of these glasses is very poor. Preservation therefore generally requires exceptionally favorable conditions (such as a sealed Egyptian tomb). As a result, natron glass of the first few centuries of the first millennium B.C. is very poorly understood, and this state of affairs is likely to persist for some time.

Written evidence that explicitly describes the process of glass production is difficult to find in the earlier periods. The civilizations of the Bronze Age have left us only two isolated Middle Babylonian texts (one of unclear date and archaeological context), and a nigh-unintelligible Hittite one, with nothing at all from Egypt. From the Iron Age, however, we are fortunate enough to have four cuneiform tablets (and several more fragments) that were collected in great library of Assurbanipal at Nineveh, the Assyrian capital of the 7th century B.C. The Nineveh tablets, which record detailed recipes for the creation of a variety of different types of glass, demonstrate the existence of a systematized body of glassmaking knowledge of considerable sophistication during the Iron Age. They describe glassmaking as a complex multiple-stage process, involving a variety of precursors that may have

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117 Reade et al. 2003, pp. 24-25.
118 Shortland et al. 2006, p. 522.
120 Oppenheim et al. 1970, pp. 32-59
included frit and faience (the meanings of many technical terms are unclear), as well as a white substance that could have been natron or crushed shell. They also specify the types of plant that should be selected to supply ash fluxes. Molten glass, interestingly, is consistently referred to as “metal.” Some of the knowledge was presumably native, and may have been preserved since Middle Assyrian times; some may have been transferred to Assurbanipal’s kingdom by the Assyrian conquest of the Levant in the late 8th century B.C., since we know that the Levantine states had produced glass for Egypt.\textsuperscript{121} One of these recipes also appears to preserve a great deal of the mysticism that surrounded Bronze Age and early Iron Age pyrotechnology, instructing the reader to choose a propitious day of a favorable month to set up the kiln, place idols around it, and sacrifice a sheep before beginning the actual glassmaking process.\textsuperscript{122} The others, however, appear to have been mostly “de-ritualized,” in Leo Oppenheim’s words, at some stage of the scribal tradition.

During the centuries corresponding to the Greek Archaic, Classical, and Hellenistic periods, glass was again worked and traded widely around the Mediterranean. The group termed “Mediterranean I” by Donald Harden is ubiquitous in the 6th, 5th and 4th centuries B.C.; striking core-formed vessels with polychrome

\textsuperscript{121} Engle 1978, p. 51; Oppenheim et al. 1970, p. 28.
\textsuperscript{122} Oppenheim et al. 1970, p. 33.
ripple or feather decoration, similar to earlier Egyptian styles, but with a different palette of colors.\textsuperscript{123} The limited range of shapes (the most common being alabastra, amphoriskoi, aryballoi, and oinochoai) appears to imitate Attic pottery, but there is presently no evidence for production in Athens. Such vessels, originally assigned to Egyptian or Phoenician production, are today believed to be mainly Rhodian (see below), though there may also have been a workshop (of uncertain location and date) producing them in Macedonia.\textsuperscript{124} “Achaemenid” glass, a class of fine, mostly colorless glass vessels related to Persian metal (and possibly rock crystal) equivalents, spawned regional variant styles around the eastern Mediterranean, most notably those centered on Rhodes, Ephesus, and Gordion (see figure 3.5).\textsuperscript{125} In Italy, core-formed glass styles characterized by rows of decorative raised knobs (\textit{stachelflaschen}), unlike anything else in the Mediterranean, attest to the existence of an Etruscan glassworking tradition.\textsuperscript{126} The production of vessel glass on the Greek mainland is less secure until the beginning of the Hellenistic period, but there is evidence for decorative architectural and sculptural elements on the Acropolis, and from the workshop of Pheidias at Olympia.\textsuperscript{127} Marianne Stern has argued for glassworking in early 4\textsuperscript{th} century B.C. Athens based on a record of a glass hydria in the inventories of the Parthenon treasury, but this notion relies on the somewhat controversial belief that υαλός always means glass in Classical Greek, and not rock crystal, unless the word is

\begin{itemize}
\item \textsuperscript{123} Harden 1981, pp. 51-54.
\item \textsuperscript{124} Weinberg and Stern 2009, p. 20.
\item \textsuperscript{125} Triantafyllidis 2001.
\item \textsuperscript{126} Towle and Henderson 2007, pp. 48-49.
\item \textsuperscript{127} Stern 2002, p. 355, pp. 360-362. Pheidias’ workshop, incidentally, provides by far the earliest evidence for the hot glass technique known as slumping (see section 2); it is possible that he invented it.
\end{itemize}
given specific qualifiers. No archaeological example of a hydria made from either material is known so early (though they do appear in glass by the end of the century).

![Image of pottery vessels](image)

Figure 3.6: Core-formed aryballos, oinochoe, and amphiorkos in the Mediterranean I style, from the Pichvnari necropolis, Georgia, 5th century B.C. Other color schemes are also known, purple trails on an opaque white ground being particularly common. After Shortland and Schroeder 2009, p. 951.

Probably the single most important location for the Greek glass industry is Rhodes, which appears to have been a major center of production and export of glass from perhaps as early as the late 6th century B.C. Mediterranean I vessels with striking stylistic affinities to examples from Rhodes itself have been found as far away as the Georgian coast of the Black Sea throughout the Classical period (see figure 3.6).

Decades’ worth of excavations at multiple Classical and Hellenistic sites on the island, mainly burials, have yielded a wealth of luxury glass vessels, including selections of both the polychrome core formed types that dominated Classical and earlier glassworking traditions, and the mosaic glass that would come to characterize later Hellenistic luxury glassworking, as well as a great deal of glass jewelry. A late 3rd to early 2nd century B.C. workshop excavated by Pavlos Triantafyllidis produced beads in forty different shapes, several kinds of monochrome vessels, and even the

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distinctive canes and beads used in the manufacture of luxurious cast mosaic glass and slumped gold-glass.\textsuperscript{130} Basins of colorants also suggest that, by this period at least, Rhodian glassworkers were capable of mixing colored glasses themselves.\textsuperscript{131} Infuriatingly, though the Mediterranean I vessels of the Classical period are extremely common on Rhodes (see figure 3.7), and it is all but certain that they were made there, a workshop matching their date has yet to be found.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.7.png}
\caption{Figure 3.7: Three Mediterranean I core-formed trefoil oinochoai, 5\textsuperscript{th} century B.C., from Ialysos, Rhodes. Note similarities to the oinochoe from Georgia above. After Triantafyllidis 2002, p. 27.}
\end{figure}

Raw glass is widely presumed to have been supplied to most of these sites by Levantine factories, though archaeological evidence is sparse, and attempts to determine locations of manufacture based on glass chemistry (see section 4) have focused mainly on the better-attested Roman period. Certainly many Hellenistic shipwrecks held large cargoes of raw glass, attesting to sea trade.\textsuperscript{132} Tantalizing potential evidence for primary glass production at a workshop in Carthage during the late 4\textsuperscript{th} century B.C. (appropriately enough, given the city’s Phoenician connections),

\textsuperscript{130} Triantafyllidis 2002, pp. 27-31; Triantafyllidis 2003, pp. 132-135.
\textsuperscript{131} Henderson 2013, p. 215.
\textsuperscript{132} Kahn 2014, p. 131.
consisting of a deposit of sand and lime, has yet to be seriously investigated.\textsuperscript{133} The excavators of the Hellenistic Rhodian workshop have noted similar deposits, also containing chunks of raw glass, though not in association with furnace fragments, which makes it difficult to associate them with primary glass production unambiguously.\textsuperscript{134} Classical Greek authors talk about glass in ways that suggest they may not even have known how it was made or what its raw materials were.\textsuperscript{135} Only around the time of the transition to Roman rule, just outside the walls of Seleucid Berytus, do we clearly see the process of making glass from its raw ingredients on an industrial scale. Here, Ibrahim Kowatli’s recent rescue excavations in downtown Beirut have uncovered four large tank furnaces that were probably active in the 1\textsuperscript{st} century B.C., and rebuilt several times in that period (see figures 2.10 and 2.11).\textsuperscript{136} Each would have been capable of producing approximately 8 tons of glass in a single firing. Other comparable facilities presumably existed, in the Levant and perhaps elsewhere, but where they are, and how early production on this scale began, is unclear.

During the Hellenistic period, though core-forming continued to exist, the popularity of the technique was waning and most glassware was cast or slumped (see section 2).\textsuperscript{137} The world’s first mass-produced glasses were types that are often described in catalogues as cast, but are more likely to have been slumped: simple monochrome round bowls (see figure 3.8), often with ribbed exteriors. These are particularly common in 1\textsuperscript{st} century B.C. Jerusalem, where they are usually colorless or the faint

\textsuperscript{133} Henderson 2013, p. 222.
\textsuperscript{134} Henderson 2013, p. 215, p. 246.
\textsuperscript{135} Stern 2007, p. 396.
\textsuperscript{136} Kowatli \textit{et al.} 2008, pp. 103-120.
blue-green of uncolored glass, but are known throughout the Hellenistic world, and often more brightly colored at other sites. Julian Henderson suggests that the mass production of glass in the late Hellenistic period was prompted by population increases, particularly in the Levant, which boosted demand, and created favorable conditions for the exploitation of more efficient techniques. These trends would only continue as the Roman Empire inherited the Hellenistic glass industry.

Glass in the Roman World

Glassworkers today remember the Romans as the inventors, or at least the evangelists, of glassblowing. Core-formed glass becomes rare in the Imperial period. Cast fine wares, usually monochrome, and often brightly colored, remain common for most of the 1st century A.D., but disappear thereafter, though the technique is revived for certain specialized wares in the late 3rd and 4th centuries A.D. Roman glass was, for the most part, blown, though the existence of both free blowing and mold-blowing provided substantial variety, and many blown types were also carved. The first blown glass was probably made in the Levant at some point during the 1st century B.C., and over the next hundred years the technology quickly spread throughout the Roman

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139 Henderson 2013, p. 250.
140 Grose 1991.
world. Well before the end of the 1st century A.D., glassblowers were established even at the opposite end of the Empire, in newly occupied Britain. The existence of regional styles implies that numerous local glassworkers were active throughout the Roman world, and sites where there is archaeological evidence for glassworking are too numerous to list. Interestingly, though, much of the compositional evidence for the Roman period suggests that most or all of these sites were supplied, as may have been the case in the Hellenistic period as well, with raw glass made by a relatively small number of Levantine (and perhaps Egyptian) sites, though in the absence of sound archaeological evidence this remains a complicated open question (see sections 4 and 5).

The earliest known archaeological evidence for blowing comes from a much-discussed refuse deposit in the Old City of Jerusalem, excavated in the 1970s by Nahman Avigad. The deposit was located in a disused ritual bath, and contained coins and potsherds that suggest a date in the second quarter of the first century B.C. More importantly for our current purposes, it contained a large number of glass fragments from every stage of what appears to be a primitive, perhaps experimental, glassblowing process. Strips or sheets of glass (some of a single color, others with streaks of different colors added in the form of glass rods) were folded into thin tubes, then allowed to cool. Once cool, one end of each tube was reheated and pinched shut; the craftsman then blew into the other (hopefully cool) end of the tube to inflate the heated end. Once the closed end of the tube had been shaped, the open end would have been clipped, leaving enough glass to form the neck and mouth of the bottle.

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The Jerusalem deposit contained some unblown glass tubes, some with partially blown globes at their ends, and a few finished or nearly-finished bottles that collapsed or otherwise failed at the last moment.\textsuperscript{144} The rudimentary technique of the first glassblowers obviously had its limitations; only very small vessels could be produced, and only minor variations on the basic globular bottle shape are evident in the Jerusalem deposit. Within a century, though, glassblowers had mastered the technique and were producing a range of vessels comparable to any assemblage of pottery or metal.

Although glassblowing was almost certainly invented in the Levant, there is reason to suspect that a number of important refinements to the craft, detailed by Stern, occurred for the first time in the western provinces. Our first experimenting glassblowers, for instance, had no archaeologically visible blowpipes; they may, as described above, have blown directly into the cool ends of glass tubes, or they may have used some kind of wooden mouthpiece to protect their lips from burns.\textsuperscript{145} Stern conjectures that, during the late 1\textsuperscript{st} century B.C. and early 1\textsuperscript{st} century A.D., when blown glass

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure39.png}
\caption{Glass amphora in the British Museum, late 1\textsuperscript{st} century to early 2\textsuperscript{nd} century A.D., from Southfleet, Kent, demonstrating the large sizes (this piece is 36.7 cm tall) achieved by Imperial Roman glassblowers. After Harden 1987, p. 96.}
\end{figure}

\textsuperscript{144} Israeli 1991, pp. 47-48.
\textsuperscript{145} Kahn 2014, p. 135.
vessels were first spreading around the Roman world, they may have been made using short, cheap terracotta blowpipes, but none of these have survived.\footnote{Stern 1999, p. 446.} We can infer that a more robust type of pipe, probably iron, must have been common by about A.D. 70, due to the increasing maximum size and weight of blown glass vessels in the western Mediterranean, particularly in Italy (see figure 3.9).\footnote{Stern 1999, p. 447.} Physical remains of these, as is often the case for iron tools, are very rare, but their telltale oxide residue on waste glass fragments appears first in a workshop in Switzerland during the second half of the 1\textsuperscript{st} century A.D.\footnote{Amrein and Hochuli-Gysel 1998.}

Glassblowers working in Italy were also probably responsible for the invention of the pontil technique, a vital staple of modern glassblowing. This term refers to the attachment of the bottom of a nearly-complete object to a metal rod (the pontil, or punty), using a blob of hot glass as glue, to allow greater flexibility in shaping the top part of the vessel, and finishing the rim, once the vessel has been cracked off the end of the blow-pipe. This leaves a distinctive scar on the bottom of the vessel. The first Roman blown glass vessels lack these marks, and the earliest known examples, again, appear in the central European provinces during the 1\textsuperscript{st} century A.D.\footnote{Stern 1999, pp. 449-450.}

The identity of the glassblowers who spread the basic technique to the west, and pioneered these innovations, is unclear. It seems likely that many of them were originally Levantine slaves; the mobility of enslaved artisans, whose skills commanded impressive prices, is thought to have been a major conduit of the spread

\footnote{Stern 1999, p. 446.} \footnote{Stern 1999, p. 447.} \footnote{Amrein and Hochuli-Gysel 1998.} \footnote{Stern 1999, pp. 449-450.}
of new technology in the ancient world.\textsuperscript{150} Glassblowers who signed their work (generally mold-blown pieces, as the signature can easily be carved into the mold) more often than not have Greek names, and many called themselves “Sidonian,” unsurprisingly, given the association of Sidon with glass in ancient literature.\textsuperscript{151} Some may well have lived and worked in Sidon, making glass vessels for export to the west, but the distribution of their products suggests that many did not. We also know of a few glassworkers with Latin names, including one woman – Sentia Secunda, who made mold-blown prismatic bottles in Aquileia during the 1\textsuperscript{st} century A.D.\textsuperscript{152} Much later, around A.D. 200, a Carthaginian-born glassworker named Julius Alexander lived, worked, and died in Lyon; the inscription from his tomb has been cited as evidence for the mobility of free craftsmen under the Empire.\textsuperscript{153}

The most famous Roman glassblower whose name is known, indeed the only ancient glassworker to whom an \textit{oeuvre} of more than a few isolated pieces can be attributed, is the early 1\textsuperscript{st} century A.D. craftsman Ennion, whose masterful mold-blown pieces prominently display his Greek signature, ENNIWN EIIOIHCE (or some variant thereof), in relief (see figure 3.10).

The signature typically appears in a \textit{tabula ansata}, a rectangular frame designed to

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\textsuperscript{150} Rihll 2013, p. 11.
\textsuperscript{151} Trowbridge 1930, p. 115.
\textsuperscript{152} Stern 1999, p. 457. Her signature includes the word FACIT, implying that Secunda was directly involved with making the bottles or their molds in some capacity, rather than being the owner or financier of the business.
give it prominence within the design, and likely inspired by contemporary use of the same pattern for signatures on Arretine pottery.\textsuperscript{154} Ennion’s Hellenized Semitic name (possibly Phoenician in origin) implies Levantine birth or ancestry, like his “Sidonian” colleagues, though he never gives us an explicit topographical reference.\textsuperscript{155} The distribution of his products, which appear all over the Mediterranean but seem most popular in northern Italy, has been taken to suggest that he spent part, if not all, of his adult life there; however, his use of Greek rather than Latin makes this an open question, and his intricate, high-quality work could easily have been exported widely.\textsuperscript{156} Ennion made a variety of cups, jugs, flasks, bowls, and beakers, in several different colors. Four other glassblowers of the same period – Meges, Aristeas, Neikais (an unusual name that may have been a feminine form of Nikias), and Jason – are considered to belong to Ennion’s “school,” and produced similar mold-blown vessels, though theirs are much less elaborately decorated, and their repertoires appear to have been much smaller.\textsuperscript{157}

The spread of glass-blowing from the place of its probable invention in the Levant corresponds with an order-of-magnitude increase in the volume of glass found at Roman sites throughout Italy.\textsuperscript{158} While glass in the Hellenistic period was a luxury good, Strabo (\textit{Geog.} 16.25) was famously able to say during the Augustan period that a simple glass bowl could be purchased in Rome for a single copper coin. As Stern observes, glass in Rome appears to have been sold conventionally by weight, so the

\textsuperscript{154} Lightfoot 2014, p. 27. As a glassblower who made extensive use of terracotta molds, Ennion would almost certainly have worked closely with potters.
\textsuperscript{155} Trowbridge 1930, p. 115.
\textsuperscript{156} Lightfoot 2014, pp. 17-21.
\textsuperscript{157} Lightfoot 2014, pp. 42-45. With the exception of Aristeas, these glassblowers only appear to have made beakers.
\textsuperscript{158} Kahn 2014, p. 136.
impact of the new technique, which was much more economical with raw materials than older methods, would have been immediate.\textsuperscript{159} Glass tablewares were probably never able to beat their pottery equivalents on price. Our go-to source for the approximate prices of commodities, the Edict of Diocletian, puts glass at more than ten times more expensive than pottery at the beginning of the 4\textsuperscript{th} century A.D. (lines 16.1-6).\textsuperscript{160} Nonetheless, once the price had been brought down from Hellenistic levels, the advantages of glass over pottery vessels would have been much more persuasive to a wider section of the population. Aside from the novelty value of a glass drinking vessel, surely a curiosity in itself for a civilization used to opaque cups, glass is not porous, as pottery is, and therefore does not absorb odors and is easier to clean. Petronius has Trimalchio offer a similar reason for preferring glass to bronze (\textit{Sat. 50}), also making note of its cheapness in comparison to metal. He even opines that he would prefer glass to gold if only it were less fragile – but, of course, Trimalchio’s opinions are best taken with a generous grain of salt.\textsuperscript{161}

There are far too many Roman glassworking sites to survey here, but one would be remiss not to mention what is easily the best known and studied: Jalame. Jalame is a villa complex in Palestine (see figure 3.11), excavated in the 1960s by Gladys Weinberg, with the particular aim of studying a site where glass vessels were made. Though the late antique villa was longer-lived, and there is also a late 1\textsuperscript{st} to early 2\textsuperscript{nd} century A.D.

\textsuperscript{159} Stern 2007, p. 384.
\textsuperscript{160} Giacchero 1974, pp. 170-171. It is, of course, unclear how representative the Edict’s prices are of market conditions in earlier periods (or even, for that matter, in Diocletian’s own time).
\textsuperscript{161} Glass, Trimalchio claims, \textit{non olibunt}; since he is here contrasting glass to metal, rather than pottery, he may mean that glass does not impart a “metallic” taste to drinks.
Figure 3.11: Location of Jalame within the Levant, after Weinberg 1988 (frontmatter). Other marked locations are sites with similar glass finds; note especially Bet She’arim, marked 1, where there is evidence for primary glass production (of uncertain date).
occupation phase, coins in the factory dump suggest that glass was only made there for some thirty years, from A.D. 351 to A.D. 383. The excavators conjecture that the operation shut down when nearby fuel resources were exhausted.162 Jalame produced enormous numbers of glass vessels during the thirty years the factory was active, and dumped so much that it seems likely the glassblowers didn’t bother to collect their waste glass for remelting, as seems to have been common practice at many other sites.163 The site produced mainly utilitarian household items, most of them free-blown, with ample evidence for the use of iron blowpipes and pontil rods. Cups, bottles, jugs, and jars make up most of the assemblage, and in each case the factory seems to have had one or two standard designs.164 Uncolored blue-green glass is the most common, but a spectrum of yellow-green, olive, and amber (probably the result of manipulation of the furnace atmosphere) is also well represented, as are colorless and purple glasses made with manganese compounds. Deep cobalt blue, and a more intense blue-green attributed to copper, are reserved mainly for decorative trails and blobs.

The complex was not devoted exclusively to glass production; in fact, the excavators also discovered wine and olive presses.165 These receive little comment in comparison to the glass finds, as they are unremarkable installations of their type, for the region and period. However, their presence illustrates that the glassblowers of Jalame did not work in isolation; the glass factory was one arm of an economic strategy that also included agricultural production. It would be natural to infer that some of the bottles made at the glass factory were meant to provide transport and

165 S. Weinberg 1988, p. 16.
storage for the villa’s output of scented oils or wine; the former is a known use for
glass bottles from early in the Imperial period, while the latter is a probable one in late
antiquity (though Jalame’s bottles are not as large as these).\textsuperscript{166} However, the variety
of shapes that seem to have been made at Jalame speaks against this being the
factory’s primary purpose. The glassblowers more likely had their own market.

In archaeometric circles, Jalame is known for the comprehensive analytical work
done at the site by Robert Brill, the preeminent figure in scientific analysis of
archaeological glass for the final third of the \textsuperscript{20}th century. His chapter of the Jalame
publication is admired for its clear understanding of his samples’ place in the site’s
history (a virtue often sadly lacking from archaeometric reports – see section 5), and
is regularly cited for a number of important points that Brill demonstrates. First, and
perhaps most importantly, as part of his analytical campaign, Brill took samples of
sand from the mouth of the River Belus (the modern Na’aman), famed in antiquity for
sand that was especially suited to glass production (see below). Analyzing these,
along with previously obtained samples of natron from Wadi Natrun, in Egypt, he
calculated that mixing the sand and natron in a ratio of 5:2 by weight, or 2:1 by
volume, would result in a glass with very similar silicon, sodium, iron, and aluminum
content to his Jalame samples.\textsuperscript{167} This suggests that the Jalame factory, and
presumably others using glass of a similar composition, was supplied with raw glass
made at a primary facility near the mouth of the Belus, perhaps in Akko-Ptolemais
(modern Acre), Sidon, or Bet She’arim (there is no archaeological evidence that
Jalame made raw glass from scratch). Second, Brill demonstrated that, even though

\textsuperscript{166} Stern 1999, p. 474, p. 479.
\textsuperscript{167} Brill 1988, pp. 265-269. In calcium content, the calculated glass composition
diverges from that of the archaeological samples, a fact that Brill attributes to the
varying amounts of shell hash in sand from different areas of the beach.
Roman glass is much more homogeneous in its composition than glass of almost any other region or period in history, there are still enough distinguishing features to group artifacts by secondary production facility, suggesting that something in the production methods can create subtly different glasses even from common materials (the presumed Acre raw glass).\textsuperscript{168} Third, Brill, together with Jan Schreurs of Corning Glass Works’ research and development labs, determined the chemicals and mechanisms responsible for translucent yellow-green and amber colors in Roman glass (see section 2). Finally, Brill measured viscosity-temperature curves for his archaeological glass samples to describe how the material’s properties were affected by heat; these tests are rarely performed due to their destructive nature, and Brill’s results provide a useful standard.\textsuperscript{169}

Aside from their more utilitarian pieces, Roman glass artisans produced a number of interesting novelty glasses. Among the best-known are cameo glasses, the class that includes perhaps the most famous Roman glass artifact of all, the Portland Vase (figure 3.12).\textsuperscript{170} These objects were produced in imitation of cameo gems, expensive and artistically demanding items made from layered semi-precious stones such as sardonyx, carefully carved to

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\textsuperscript{168} Brill 1988, pp. 258-264.
\textsuperscript{169} Brill 1988, p. 279.
\textsuperscript{170} Harden 1987, pp. 58-67.
reveal the different layers of color in the material. Cameo glass is layered glass, carved to achieve a similar effect, harking back to earlier conceptions of glass as a sort of artificial gem. The vast majority of all Roman cameo glass is dated on stylistic grounds to the early Julio-Claudian period; there appears to have been a minor revival at the end of the 3rd century A.D. It is rare in both periods, with fewer than twenty complete or restored vessels and some two hundred sherds known worldwide. Pieces of Roman cameo glass are overwhelmingly attributed to Italian sites (with varying degrees of certainty, as many spent decades or centuries in private ownership), so they are generally thought to have been made in Italian workshops from raw glass imported from Egypt and the Near East, although some production in Egypt itself is also possible.

Most Roman cameo glass is thin enough that it must have been blown, probably through a technique known today as “flashing,” in which a blob of glass of the background color, gathered on the end of a blow-pipe, is dipped into a crucible of molten glass of the foreground color to coat it; the two layers are then blown together. The layering of glasses with slightly different compositions greatly increases the risk of thermal shock, as the two will contract at slightly different rates as the glass cools; the implied technical proficiency, at such a relatively early point in

171 Augustus himself is often said to have had a particular fondness for cameo-cut stone and glass, based on items like the Gemma Augustea, and an anecdote in Suetonius (Aug. 71) that claims a cameo-cut stone bowl was the only item he kept for himself from Cleopatra’s treasury in 31 B.C. It would here be a grievous act of deprivation against the reader not to mention Kenneth Painter and David Whitehouse’s triumphant conclusion (Painter and Whitehouse 1991), after a careful examination of the Portland Vase’s famously impenetrable mythological motifs, that the unique cameo glass urn “can only have belonged to Augustus himself.”
the history of glassblowing, is quite impressive. The majority of Roman cameo glass has two layers; commonly a blue or purple background and a white foreground, the latter often containing lead to soften it for carving, in much the same way as modern lead crystal. However, exceptional pieces with as many as six different colored layers also exist.\textsuperscript{175}

When discussing Roman glass from a chemical perspective, it is difficult not to mention another novelty piece: the famous and unique artifact known as the Lycurgus Cup, which like the Portland Vase currently resides in the British Museum.\textsuperscript{176} This goblet is an example of an elaborate, phenomenally labor-intensive form of 4\textsuperscript{th} century A.D. cast, carved, and ground glass known as a cage-cup or diatreta, a cup surrounded by a delicate lattice of carved glass. It is also the only complete specimen of a Roman artifact made from dichroic glass: a glass which reflects light of one color but transmits light of a different color, so that its color changes when it is held up to a light source.\textsuperscript{177} The Lycurgus Cup appears pea green and opaque normally (figure 3.13), but a brilliant translucent scarlet when light shines through it (figure

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{figure3.13.jpg}
\caption{The Lycurgus Cup as it appears in reflected light. After Harden 1987, p. 246.}
\end{figure}

\begin{thebibliography}{9}
\bibitem{175} Harden 1987, p. 53.
\bibitem{176} Harden 1987, pp 245-249.
\bibitem{177} Elsner 2013, p. 103.
\end{thebibliography}
3.14). Inevitably, it has attracted a great deal of interest from archaeometrists hoping to explain this phenomenon.

The Cup’s seemingly magical properties are the result of a clever manipulation of colloidal gold and silver. Finely divided particles of a mixture of gold and silver, on average 70nm in diameter, are dispersed evenly throughout the glass matrix. The glass’s opacity in reflected light results simply from the scattering of light by the crystalline particles, functioning in a similar way to other opacifiers such as antimonate colorants (see section 2). More intense light shining through the glass is instead colored red by absorption in the blue region of the spectrum. This property is exhibited only by gold nanoparticles, not by bulk gold (which is, of course, bright yellow), due to the interaction of the so-called noble metals’ unique electrical properties with light. If the particles in the glass were significantly larger, the opacifying effect would dominate under all conditions; if they were significantly smaller, the absorption would dominate, as in the early modern formulation known as gold-ruby glass. Only a very particular size range, with homogeneous particle size and distribution, could have produced the effect we see. It

178 Barber and Freestone 1990.
was probably made by introducing the precious metals to the glass melt in some oxidized form. This would have allowed the dissolved metals to spread evenly throughout the mixture before they were reduced to insoluble metallic form by reaction with any of the several transition metals commonly present in soda-lime glass. Crystals of gold and silver would then have nucleated simultaneously throughout the glass matrix, growing at an even rate, creating the necessary homogeneous distribution.

The nature of the gold source in the Lycurgus Cup is a problem. Gold is extremely unreactive, hence its value as a medium for storing wealth, and it is therefore difficult to find in compounds. Early modern gold-ruby glasses seem to have been made using colorant solutions like “Purple of Cassius,” which were prepared with aqua regia (a frighteningly potent solvent consisting of a mixture of hydrochloric acid and nitric acid, which can actually dissolve gold to produce chloroauric acid, HAuCl₄). However, no ancient sources indicate familiarity with this reagent, or indeed anything capable of dissolving metallic gold. Accordingly, David Barber and Ian Freestone suggest that metallic

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180 Barber and Freestone 1990, pp. 42-43.

Figure 3.15: One of the few other pieces of Roman dichroic glass, a fragment of a 4th century A.D. cage-cup in the British museum, in reflected light (above) and transmitted light (below). Image after Freestone et al. 2007, p. 271.
gold was added directly to the melt, and that the homogeneity required by the dichroic effect was instead achieved by several stages of crushing, grinding, and re-melting.\textsuperscript{182} The idea that such a laborious manner of producing the effect could have been discovered by accident strains credulity, and I am more inclined to believe that a rare few Roman glassmakers had performed unattested experiments with something resembling aqua regia. Admittedly, though, the sheer rarity of dichroic Roman glass, together with the relatively poor quality of all known pieces other than the Cup itself (see figure 3.15), may imply that the method of its production was far from refined.

The glassmaking traditions of the Roman Empire and its Hellenistic forerunners did not end with the expiry of the western half of the Empire, but were inherited by the Byzantine Empire along with the core glassmaking regions of the Levant, which continued to supply raw glass to Europe throughout late antiquity. In western Europe, the “golden age” of Roman glassmaking had been the High Imperial period, but the corresponding high point of diversity and quality in the eastern Empire is in late antiquity.\textsuperscript{183} Perhaps the most distinctive development of the Byzantine period is an increased appreciation for the optical properties of glass, in the form of the introduction of glass lamps.\textsuperscript{184} These are very different from the terracotta lamps with which Greek and Roman archaeologists will be familiar, generally having an open bowl shape, sometimes with a wick tube at the center, and often three handles that allow them to hang by chains from a hook. They are among the most common glass forms in the early Byzantine period, and appear in a wide variety of contexts. In addition, glass mosaics, already quite common in the Roman period, rise to become

\textsuperscript{182}Barber and Freestone 1990, pp. 43-44.
\textsuperscript{183}Stern 1999, p. 481.
\textsuperscript{184}Gorin-Rosen and Winter 2010, p. 172.
“a Byzantine medium *par excellence*” (albeit a criminally understudied one, in both periods).\(^{185}\)

From a compositional perspective, the “end” of the broad group of chemically similar ancient glasses that includes those of the Roman Empire comes at some point in the late 9\(^{th}\) century A.D. At this point, the natron supplies of Egypt (whose production capacity is thought to have been under strain due to political upheavals in the region since the early 7\(^{th}\) century A.D.) ceased to provide the main alkali source for both Islamic and European glasses.\(^{186}\) Likely in response to difficulty in acquiring natron in sufficient quantities, the Near East switched to glasses based on halophytic plant ash like those produced in the Bronze Age and in the Parthian and Sassanid Empires, while western Europe began to focus primarily on the high-potassium wood ash glasses (known as *waldglas*, or “forest glass,” for the source of the flux) typical of the Mediaeval period. Interestingly, there is a minority Byzantine tradition in western Anatolia that appears to have continued using natron well into the 12\(^{th}\) century A.D., apparently exploiting an unknown source with sodium borate (Na\(_2\)B\(_4\)O\(_7\)) as a major impurity; however, this is an unusual exception.\(^{187}\) From the 7\(^{th}\) century A.D. onward, glass seems to have become much less common in what remained of the eastern Empire than it was in earlier periods, and Middle Byzantine glass in general shows a heavy debt to Islamic styles and forms.\(^{188}\)

\(^{185}\) James 2008.  
\(^{186}\) Shortland *et al.* 2006, p. 527.  
\(^{187}\) Rehren *et al.* 2015, pp. 276-277.  
\(^{188}\) Stern 2010, pp. 114-117.
Glass in Roman Literature

Ancient glass is not often studied from a philological perspective, and archaeological and archaeometric studies rarely discuss textual evidence for glass production more than superficially. Even today, the most complete and detailed work on glass in ancient literature is arguably Mary Trowbridge’s *Philological Studies in Ancient Glass*, published in 1930. Only a few Roman period texts talk about glass, or its manufacture, at any length, though many mention it in passing, and from these we can perhaps derive an impression of how people generally thought about glass. The fullest discussion of the material in extant Roman literature comes from the *Natural History* of Pliny the Elder, to whom the bulk of this section will accordingly be devoted.

Trowbridge discusses at some length the use of the adjective *vitreus* or *vitrius* – glassy – in Latin poetry. As well as being applied to objects that are actually made of glass, the word is commonly used by analogy to mean “bright,” “shining,” or “transparent.” Sometimes it appears to denote a sea-green color, not unlike the hue of most uncolored Roman glass. It can also carry connotations of fragility or even fickleness; Horace (*Carm.* 1.17.20) calls the sorceress Circe *vitrea*, while other texts give the same epithet to fame, wealth, pleasure, and life. We might compare here Trimalchio’s oft-quoted, and probably exaggerated, comments on the superiority of glass to bronze in the *Satyricon*, already mentioned above, which may illustrate a cultural association of glass, at least in the 1st century A.D., with the tasteless *nouveau*

189 Stern 2007, p. 342.
190 Trowbridge 1930, pp. 68-76.
Glass is attractive, and shines like metal, but it does not endure, shattering even more readily than pottery – and, of course, it is cheap.

A few late antique laws concerning glassworkers are also recorded, mainly courtesy of Byzantine legal compendia. Most of these concern taxes, or exemptions therefrom, affecting artificers generally, not glassworkers specifically, and are not particularly interesting. One that is worth mentioning is a Byzantine law effective in Palestine (therefore early 7th century A.D. at the latest), which instructed glass- and metalworkers to do their work outside of cities if at all possible, or at least to avoid densely populated areas. The aim of the law, explicitly, was to reduce the risks of fire (a perennial concern in crowded ancient cities) and sickness. Similar restrictions are likely to have applied in earlier periods.

The most extended discussion of glass we have from antiquity is found in book 36, chapters 65-67 of Pliny the Elder’s *Natural History*; a text and translation of these chapters are included below. Pliny is an excellent source in his way; for many aspects of Roman science, industry, and technology he is our most detailed (sometimes our only) literary source. However, like any ancient source he is not without his flaws. While his breadth of knowledge is admirable and many of his broader statements accord well with archaeological evidence, it would be a mistake to regard Pliny’s testimony on craft technologies as expert, in all or even many of the fields on which

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191 Trowbridge 1930, pp. 118-119 summarizes these.
192 Trowbridge 1930, p. 119.
193 See Fischer 2008, pp. 140-148 for a summary of the range of illnesses associated with traditional glassblowing, many of which might also affect people living near a workshop.
194 Henderson 2013, p. 208.
he comments.\textsuperscript{195} Moreover, the terminology he uses for materials of all kinds is, typically enough for the ancient world, often imprecise in comparison to modern scientific nomenclature. Despite modern admiration of his zeal in recording the eruption of Vesuvius, showing a devotion to scientific inquiry that ultimately led to his death, it is also unclear how much of the \textit{Natural History} is based on his own firsthand observations.\textsuperscript{196} A great deal more of it is likely culled from earlier scientific texts, many of which are now lost to us. Having said that, it is clear that Pliny was exceptionally well read, as the list of citations he helpfully provides at the end of each book makes clear, and exploited the intellectual resources of the Roman Empire to the greatest possible extent.

\textbf{Pliny the Elder, \textit{Natural History} 36.65-67}


\begin{quote}

\textit{65: Pars Syriae, quae Phoenice vocatur, finitima Iudaeae intra montis Carmeli radices paludem habet, quae vocatur Cendebia. Ex ea creditur nasci Belus amnis quinque milium passuum spatio in mare perfluens iuxta Ptolemaidem coloniam. Lentus hic cursu, insaluber potu, sed caerimoniiis sacer, limosus, vado profundus, non nisi refuso mari harenas fateitur; fluctibus enim volutatae nitescunt detritis sordibus. Tunc et marino creduntur adstringi morsu, non prius utiles. Quingentorum est passuum non amplius litoris spatium, idque tantum multa per saecula gignendo fuit vitro. Fama est adpulsa nave}
\end{quote}

\textsuperscript{195} Purely by way of example, witness his insistence (\textit{HN} 33.57) that Egyptian Blue (\textit{caeruleum} in Latin) is made by dyeing sand with the extract of a special plant (which he does not name), a statement refuted from every angle imaginable, including chemical analyses, experimental archaeology, and the contrary testimony of Vitruvius.

\textsuperscript{196} Murphy 2004, pp. 3-11.
mercatorum nitri, cum sparsi per litus epulas pararent nec esset cortinis attollendis lapidum occasio, glaebas nitri e nave subsidisse, quibus accensis, permixta harena litoris, tralucentes novi liquores fluxisse rivos, et hanc fuisse originem vitri.

66: Mox, ut est ingeniosa sollertia, non fuit contenta nitrum miscuisse; coeptus addi et magnes lapis, quoniam in se liquorem vitri quoque ut ferrum trahere creditur. Simili modo et calculi splendentes multifariam coepti uri, dein conchae ac fossiles harenae. Auctores sunt in India et crystallo fracta fieri et ob id nullum conparari Indico. Levibus autem aridisque lignis coquitur addito Cyprio ac nitro, maxime Ophirio. Continuis fornacibus ut aes liquatur, massaeque fiunt colore pingui nigrantes. Acies tanta est quacumque, ut citra sensum ullum ad ossa consecet quidquid adflaverit corporis. Ex massis rursus funditur in officinis tingiturque, et aliud flatu figuratur, aliud torno teritur, aliud argenti modo caelatur, Sidone quondam his officinis nobili, siquidem etiam specula excogitaverat. Haec fuit antiqua ratio vitri. Iam vero et in Volturlo amne Italiae harena alba nascens sex milium passuum inter Cumas atque Liternum, qua mollissima est, pila molave teritur. dein miscetur tribus partibus nitri pondere vel mensurae in alias fornaces transfunditur. Ibi fit massa, quae vocatur hammonitrum, atque haec recoquitur et fit vitrum purum, massa vitri candidi. Iam vero et per Gallias Hispaniasque simili modo harena temperamentur. Ferunt Tiberio principe excogitato vitri temperamento, ut

197 Many editors here amend Ophirio to Aegyptio, which makes far more sense given what we know of the natron industry, but the manuscript tradition is in fact quite firm on this point. Ophir is mentioned in passing in a number of texts, but its location eludes all attempts at rational deduction; James Innes Miller once argued (Innes Miller 1969, pp. 260-267) that it was in fact the Phoenician name for, of all places, Malaysia.
flexile esset, totam officinam artificis eius abolitam, ne aeris, argenti, auri metallis pretia detrherentur, eaque fama crebrior diu quam certior fuit. Sed quid refert, Neronis principatu reperta vitri arte, quae modicos calices duos, quos appellabant petrotos, HS VI venderet?

67: In genere vitri et obsiana numerantur ad similitudinem lapidis, quem in Aethiopia invenit Obsius, nigerrimi coloris, aliquando et tralucidi, crassiore visu atque in speculis parietum pro imagine umbras reddente. Gemmas multi ex eo faciunt; vidimus et solidas imagines divi Augusti, capti materiae huius crassitudine, dicavitque ipse pro miraculo in templo Concordiae obsianos quattuor elephantos. Remisit et Tiberius Caesar Heliopolitatum caerimonis repertam in hereditate Sei eius, qui praefuerat Aegypto, obsianam imaginem Menelai, ex qua apparat antiquior materiae origo, nunc vitri similitudine interpolata. Xenocrates obsianum lapidem in India et in Samnio Italiae et ad oceanum in Hispania tradit nasce. Fit et tincturae genere obsianum ad escaria vasa et totum rubens vitrum atque non tralucens, haematinum appellatum. Fit et album et murrina aut hyacinthos sappirosque imitatum et omnibus aliis coloribus, neque est alia nunc sequacior materia aut etiam picturae accommodatior. Maximus tamen honos in candido tralucentibus, quam proxima crystalli similitudine. Usus vero ad potandum argenti metalla et auri pepulit. Est autem calor inpatiens, ni praecedat frigidus liquor, cum addita aqua vitaeae pilae sole adverso in tantum candescant, ut vestes exurant. Fragmenta teporata adglutinantur tantum, rursus tota fundi non queunt praeterquam abruptas sibimet in guttas, veluti cum calculi fuint, quos quidam
65: That part of Syria which borders on Judaea, and is known as Phoenicia, contains a marsh called Cendebia lying amid the foothills of Mount Carmel. This is believed to be the source of the river Belus, five miles long, which flows into the sea close to the settlement of Ptolemais. Its course is sluggish, and its water unsavory but hallowed. Muddy and deep, it yields its sand only when the tide ebbs, and the sand, from which all impurities have been washed away by the tossing of the waves, sparkles in the sun. Then only is the sand thought fit for use, when it has been subjected to the mordant saltiness of the sea. The shore does not exceed half a mile in extent, and yet, for long ages, it was the only source of sand for making glass. The story is that merchants put in there with a cargo of crude soda, and when, scattered over the beach, they were preparing a meal and could find no stones of the right height to prop their pots, they supported them on lumps of soda which they had fetched from the ship. When these were melted by the heat and mingled with the sand, transparent streams of a strange liquid were seen to flow, and thus glass was discovered.

66: The restless ingenuity of man was not long content to make glass from sand and soda only. He began to add the magnet stone also, for to it is attributed the property of attracting, not only iron, but also molten glass. Similarly, shining pebbles of many sorts were added to the melt, and then shells, and sands dug out of the earth. Some authorities state that in India glass is made from fragments of rock crystal, for which reason Indian glass is beyond compare. In
making glass, a fire of light, dry wood should be used, and Cyprian copper added, and soda, preferably that of Ophir. The smelting of glass should be done, like that of copper, in a series of furnaces. Masses of a rich, dark color are obtained. Molten glass is, for some reason, so penetrating that, before there is time to realize what is happening, it cuts to the bone any part of the body which it touches. These masses are again melted by the workmen and coloring matter is incorporated. Then the glass is shaped by blowing, or turned upon a wheel, or, again, engraved as if it were silver. Sidon was once famous for manufacturing glass, and indeed mirrors were first invented there. Such was the old method of making glass. Now the Italian river Volturnus also furnishes a white sand which is found for six miles along the seashore, from Cumae to Liternum. This sand is very soft, and is ground in mortars or between millstones. It is then mixed with three parts of soda, by weight or measure, brought to a state of fusion, and transferred to another furnace, in which a mass called *hammonitrum* is formed. This is fused a second time and *vitrum purum* is obtained, a mass of colorless glass. Similar methods are now in vogue in the Gauls and Spains for converting sand into glass. The tale is told that, during the reign of Tiberius, a glass was devised, so compounded as to be flexible, and that the workshop of the inventor was utterly destroyed, lest there should be a decline in the value of copper, silver, and gold. The story has hardly been well-authenticated enough to warrant the publicity which it has long received. This matters little, however, for, in Nero’s reign, a technique of glass-working was developed which made it possible to obtain 6,000 sesterces for two small cups of the kind called *petroti*. 
67: Under the heading of glass are included *obsiana*, named from their similarity to the stone which Obsius found in Aethiopia. This stone is very dark in color, sometimes translucent, but more opaque than glass, and if a mirror of it is placed upon a wall, shadows rather than images appear therein. Many use it in jewellery, and we have even seen it used for solid statues of the emperor Augustus, who was fascinated by this opaque material, while he himself dedicated four obsian elephants, as a rare treasure, in the temple of Concord. Moreover, Tiberius Caesar restored to the people of Heliopolis a sacred image of Menelaus, made in obsian, which had been found among the property left by one Sejus who had been ruler of Egypt. This shows that the material, whose resemblance to glass has caused the transference of its name, is really of much earlier origin. Xenocrates is our authority that the obsian stone occurs in India, in the district of Italy called Samnium, and in the part of Spain which verges on the Ocean. By a coloring process, an artificial obsian glass is prepared, of which vessels for the table are made, and an opaque glass which is red all through, called *haematinium*, is similarly manufactured. There are made also a white variety, glasses which resemble in color murrhine objects, the hyacinth, and the sapphire, and in fact glasses of every color. We possess no more tractable material, and none which is more suitable for mosaic patterns. For all that, the glass which holds pride of place is colorless and transparent, as like crystal as possible, and this has displaced gold and silver as a material for drinking-vessels. Glass vessels, however, will not withstand heat, unless they have first been filled with cold water, although, on the other hand, a glass globe full of water, if placed over against the sun, becomes hot enough to set garments on fire. Pieces of broken glass, when heated, can be joined together, but not
completely melted except into scattered globules, as in the making of those marbles which are named from their resemblance to an eye, and are often colored in the most varied manner. When glass is heated with sulfur, it hardens into stone.

Discussion

The location within the *Natural History* of the passage on glass is interesting in itself. Earlier civilizations, as we have seen, seem to have regarded glasses as artificial gemstones; however, Pliny deals with precious stones in book 37, the final volume of the encyclopedia, instead placing glass (along with obsidian, which is *in genere vitri*) in book 36. This book’s stated topic is stone, though it focuses particularly on marble, and hence contains a great deal on sculpture, architecture, and famous buildings. It also describes a variety of stones with miscellaneous interesting properties (such as the famous magnetic stones of Magnesia). Pliny segues into glass by way of its use in ceiling mosaics, which he considers a recent development, and discusses in chapter 64. He also recalls here an anecdote he discussed earlier (*HN* 36.24) about a late Republican theatre with a three-tiered *scaena*, whose middle tier was supposedly built entirely out of glass, an extravagance that he described as *inaudito etiam postea genere luxuriae*. After his discussion of glass and obsidian, Pliny moves on to a wondering description of the transmutative powers of fire (including its ability to turn sand into glass) in chapter 68. The position of the glass chapters thus stresses Roman innovation in the use of the material, often to excessively luxurious ends, as well as its interesting status as an artificial material created by the almost magical effects of fire.
In *Natural History* 36.65, Pliny claims that the first glass was produced by accident by a group of seafaring merchants. Cooking their dinner on a beach near the mouth of the river Belus in Phoenicia, the merchants could find no stones to support their cauldron and instead used lumps of *nitrum* (probably Egyptian natron), and were surprised to find rivulets of molten glass forming from the sand around their fire. One might be forgiven for passing over this account as barely-historical hearsay. If nothing else, it seems unlikely that the temperatures required for fusing a mixture of silica and natron, well in excess of 1000 ºC, could be achieved by accident on an open-air cooking fire.\(^{198}\) However, it certainly attests to the strong geographical association of the glass industry with the Levant in Roman minds during Pliny’s time.

Engle finds evidence in several different written sources (albeit of varying relevance and persuasiveness) for the importance of the Belus area specifically for the production of raw glass throughout classical antiquity and well back into the Bronze Age, perhaps suggesting that Pliny may have hit on a traditional account of genuinely great age.\(^{199}\) Julian Henderson, likewise emphasizing the story’s probable status as a “tradition,” suggests that the combination of sand and fuel ash from a cooking fire on a beach might be less of a stretch than Pliny’s version (and would also be compatible with an ultimate origin for the story that predates the common use of natron in glass).\(^{200}\)

Other Greek and Latin sources confirm the importance of this particular section of the Levantine coast, at least in the Roman period, for glass production, though the story

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\(^{198}\) Pollard and Heron 1996, p. 158.
\(^{199}\) Engle 1978, throughout.
\(^{200}\) Henderson 2013, p. 51.
of the natron merchants appears only in Pliny. Strabo (Geog. 16.2.25) refers to a
beach “between Acre and Tyre,” but explains that the sand is actually taken to Sidon
to be melted. He also notes that, according to some, usable sand can be obtained at
Sidon itself, while others claim that any sand will suffice. Strabo does not mention
natron, though he does make reference to the creation of colored glasses using
mineral additives, locally available in Alexandria and Rome. Tacitus (Hist. 5.7)
mentions the Belus by name, and refers to the use of nitrum, but gives us nothing
more. There is also a somewhat confusing passage of Josephus (BJ 2.10.2) that
describes a round hollow in the ground near the river, where ideal glassmaking sand
was deposited by the wind. Brill thought that he might have found this hollow when
he investigated the area during the Jalame excavations, though he notes that the
topography of the beach may have been altered by modern construction.\footnote{Brill 1988, p. 266.} There
may well be something to Josephus’ description, as Brill’s samples revealed variation
in the major element composition of the sand of different zones of the beach, created
by the action of wind and water, which would have materially affected the properties
of any glass made from it. Ancient glassmakers may have discovered, by trial and
error, that one specific part of the beach was optimal, though it is difficult to see any
way of confirming this archaeologically or geologically.

After finishing the natron merchants’ tale, the origo vitri, Pliny goes on to explain that
a variety of other ingredients soon came to be added to glass mixtures, ut est
ingeniosa sollertia, non fuit contenta nitrum miscuisse – that is to say, in a spirit of
experiment. This description probably says more about how Pliny views
technological change generally than about Roman glassmakers. He mentions calculi
splendentes, shining stones, and it seems likely that this refers to some of the various substances that give glass its brilliant colors, most of which were introduced in the Late Bronze Age. Pliny’s grasp of the actual history of the development of glass recipes is probably extremely vague. Clearly, though, he thinks of glass, and the many different recipes for it, as a good example of human ingenuity.

This section also mentions the addition to glass of a substance called magnes lapis. Pliny’s descriptions elsewhere (HN 34.42 and 36.25) make it abundantly clear that by this he usually means magnetite (iron II-III oxide, Fe₃O₄), which took its name from the central Greek region of Magnesia, and was famous in the ancient world for its magnetic properties. However, there is no evidence that magnetite was ever an ingredient in general recipes for Roman glass, nor any convincing reason why it would be. Many commentators suggest that Pliny may have become confused by a reference to Magnesian limestone (μαγνητικός λίθος in Theophrastus, On Stones 41), which would at least make sense from a chemical perspective as a source of calcium for the glass mixture. However, the weight of the evidence generally seems to favor the incorporation of calcium into Roman glass in the form of crushed shells (conchae, another optional ingredient mentioned by Pliny) in beach sand, not as limestone. Pliny’s own explanation is that glassmakers tried it because “to it is attributed the property of attracting, not only iron, but also molten glass,” which raises more questions than it answers. In fact, Natural History 36.25 describes several other stones, not all of them magnetic, to which the name magnes lapis was sometimes applied. As such, I am rather inclined to favor the minority view that the magnes

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202 Healy 1999, p. 353; Trowbridge 1928, p. 100. Pliny himself clearly believes that he is talking about magnetite, since he also mentions glass in connection with Spanish magnetic stones in Natural History 34:148 (though only to mention that, to his knowledge, no-one has ever tried making glass with this variety of the substance).
lapis used by Pliny’s glassmakers should be identified with another lustrous black stone that was common in Magnesia, namely the manganese ore pyrolusite (MnO₂). Manganese was in common use as a decolorant in Roman glass (see section 2), and colorless glass was popular and valuable in Pliny’s time. Pyrolusite is the most likely candidate for the raw ingredient that supplied it, as indeed it was in the early modern glass industry. Pliny may well have misunderstood what was meant when he was told of “Magnesian stone” being added to glass batches, assuming that his source was referring to the obviously superior magnetic variety.

Pliny next describes the melting of the ingredients in continuis fornacibus into massae nigrantes (in just the manner in which glass appears to have been produced in tank furnaces like those at Beirut), followed by the reheating of pre-prepared raw glass for coloring and working. This could be taken to imply that the addition of colorants was, at least some of the time, the task of secondary workshops rather than primary producers of glass, which seems to accord with Strabo’s vague mention of vitreous substances used for the production of colored glass at Rome and Alexandria. Pliny also mentions copper among the raw ingredients of the initial batch, however he does not appear to be aware that the metal is included as a colorant. The methods he describes for working glass in the second stage include flatu figuratur (obviously a reference to blowing), torto teritur and argenti modo caelatur. Traditionally the latter two are translated as some variant of “turning on a lathe” and “engraving.” Stern instead favors interpreting the former as describing a slumping technique using a device like a potter’s wheel to shape the hot glass, though this has been contested by Alysia Fischer on the grounds that no such device has ever been found in an ancient

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203 Trowbridge 1928, p. 100.
204 Brill 1988, p. 276.
glass workshop, and that Stern’s experimental bowls have much thicker walls than the ancient designs they imitate. The latter technique Stern takes to be a reference to the glassworking technique that most closely imitates engraved silverware – namely blow-molding.

What follows is one of the more contentious aspects of Pliny’s account of Roman glassmaking: his assertion that in his time glass was made – not just worked, but made from its raw ingredients – in Campania, Gaul, and Spain. He makes specific reference to the fine white sands of the mouth of the river Volturnus, some 25 km up the coast from the Bay of Naples. Archaeological evidence for such production is at present nonexistent. It is tempting to think that Pliny is simply mistaken, and that these operations were secondary workshops using imported raw glass, but the specificity of his reference to the sands of the Volturnus would then be bizarre. More to the point, while it is easy to imagine that he could make mistakes of this nature when discussing the far end of the Roman Empire, of which his knowledge was probably secondhand, it is much harder to think that he could be equally wrong about Campania – which, let us remember, is where he lived. Absence of evidence should not, in this case, be taken as evidence of absence.

The sand of the Campanian littoral, in its natural state, can be shown to be unsuitable for glass production; the resulting glass has inferior chemical resistance and is compositionally inconsistent with the vast majority of characterized Roman glasswares, being much too high in calcium and aluminum. However, Alberta

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205 Fischer 2008, p. 64.
207 Kahn 2014, p. 132.
Silvestri et al., in a study of sand samples from the coast of Campania, were able to develop a method of modifying the sand before fusion to improve the quality of the resulting glass, based on Pliny’s text, and using only technology that would have been available in the Roman period. The key here is the precise meaning of the phrase *qua mollissima est* (“where [the sand] is softest”). In fact *mollis* has a technical sense specific to geology, where it can be used to describe “soft” stone (as opposed to *temperata* or *dura* stone), a classification Pliny has likely learned from Vitruvius (whom he cites in book 36). Silvestri et al. believe that it means here that the sand contained a larger than usual proportion of soft, friable rocks like limestone, as opposed to harder stones like feldspar. Moreover, *qua mollissima est* is not a description of the whole Campanian coastline, but rather a prescription to seek out the specific points on the coast at which the sand was “softest.” The grinding of the sand with a mortar and pestle, as Pliny describes (*pila molave teritur*), can strip out the “soft” portions and leave behind the silica, creating a purer sand that is much more suitable for glass. The same can be done with “harder” sand, but the process takes longer and the yield is lower. What Pliny describes is therefore not inherently infeasible.

Pliny’s next anecdote on glass is perhaps somewhat less likely to have a basis in fact; he himself feels that the story is *fama crebrior... quam certior*. During the reign of Tiberius, he tells us, an unnamed genius artificer discovered a *temperamentum* (a mixture or recipe) that made *vitrum flexile* – flexible glass. A more detailed and dramatic version of the same story is told by Trimalchio in the *Satyricon* (chapter 51), in which the inventor deliberately throws a glass cup on the floor, to the horror of the...

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208 Silvestri et al. 2006.
Emperor (whom Petronius does not name), only to reveal that it is merely dented and can be repaired with a hammer, just like a metal vessel. In both versions, the Emperor responds out of fear that the existence of flexible glass will dramatically devalue precious metals. Pliny says that he destroyed the glassmaker’s workshop; Petronius (in characteristically lurid fashion) reports the glassmaker’s summary decapitation. There is unlikely to be any truth to the story at all; flexible glass is beyond the wildest dreams of even modern materials science. Stern explains the tale as a flagrantly embellished retelling of an unremarkable anecdote about a glassworker skillfully repairing a glass vessel that was dented while it was still hot and pliable. However, the extreme reaction, in both cases, is potentially an interesting comment on ancient opinions about the value of glass. Pliny seems to have felt so too, for he immediately asks *quid refert?* and describes the invention, in the time of Nero, of a particular *ars vitri* used for making two fabulously expensive cups called *calices petroti*. These cups, he tells us, sold for six thousand sesterces apiece.

After a short discussion of obsidian (see section 2), Pliny concludes his section on glass with a short list of general facts about the material. There is, he says, no substance that is easier to shape or to color, though the *maximus honos* is afforded to colorless glass that resembles rock crystal; later on (*HN* 37.29) he observes that, perversely, the availability of this has only increased the value of true rock crystal. He claims that glass has displaced (*pepulit*) silver and gold as a material for drinking.

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210 A slightly different, but clearly related, anecdote is told by Cassius Dio (57.21); here the inventor is an architect, whom Tiberius had already exiled for an unrelated offense, and he appears to restore the vessel with his hands alone. As in Petronius, the poor man is immediately executed.

211 Stern 2007, p. 357.

212 Exactly what the *calices petroti* are is unclear, but André *et al.* 2003, p. 246 believe that the name implies imitation of a form normally executed in rock crystal.
vessels (perhaps lending a shade more credibility to Trimalchio’s words on the subject); we know, of course, that metal drinking vessels did not disappear in the 1st century A.D., but the point is surely that well-made glassware was able to compete as an elite product, even as glass became more and more cheaply available throughout the Empire. He notes that glass vessels filled with water can focus the rays of the sun and start fires; a similar use is made of a glass lens in a scene from Aristophanes’ *Clouds* (lines 765-772).\(^{213}\) He explains that, although broken pieces of glass can be joined (*adglutinatur*) by heat, they cannot be remelted completely, which Stern takes to mean that the recycling of glass was largely unknown, at least in the western half of the Empire, before the 70s A.D.\(^{214}\) Finally, and bizarrely, Pliny claims that when glass is made with sulfur it becomes as hard as stone. Almost all Roman glass does contain small amounts of sulfur, probably an impurity derived from Egyptian natron.\(^{215}\) However, its solubility in silica is poor, there is no evidence that it was ever added deliberately, and there is certainly none that it would produce the effect Pliny describes.

Pliny’s description of glass production under the Empire hints at a belief in steady technological progression.\(^{216}\) Chapters 65 and 66 are roughly organized according to chronology. He describes first the *origo vitri*, the somewhat fanciful tale of the merchant sailors. The following section mentions variations that were made in the

\(^{213}\) It is unclear whether ὑαλός here means glass or rock crystal, though I believe the former is likely; see Stern 2007, pp. 371-372.

\(^{214}\) Stern 1999, p. 451. Statius (*Silv.* 1.6.73-74), Juvenal (*Satires* 5.47-48), and Martial (*Epigrams* 1.41 and 10.3) all make clear reference to the collection of cullet for recycling, and it is likely to have become common in the years shortly after Pliny’s death in A.D. 79.


\(^{216}\) Thanks are here owed to my colleague Kyle Helms for some stimulating discussions on Roman perceptions of technical knowledge.
recipe for glass, *ut est ingeniosa sollertia*, and describes Pliny’s conception of the glass industry as it was when it was centered at Sidon, including the use of tank furnaces like those we know from the archaeology of the Roman Levant. This, he concludes, is the *antiqua ratio vitri*. His subsequent description of glass production at the mouth of the Volturnus, by contrast, is explicitly presented as a recent development, a feature of his own time. Finally, he describes two specific Roman innovations, with reference to the times at which they took place: the *temperamentum* that resulted in flexible glass, under Tiberius, and the new *ars vitri* used for making the *calices petroti*, under Nero. To Pliny, the establishment of primary glassmaking facilities in Italy, Gaul, and Spain represents part of the same sequence of technological development as these innovations. Tiberius’ somewhat violent reaction to the new technology in the flexible glass story, when it is commented on, tends to be seen as exemplifying general Roman resistance to technological progress.\(^{217}\) Both Pliny and Petronius cite as his motivation a fear that the wondrous material’s existence would lead to the devaluation of precious metals like gold. The Emperor is portrayed as wanting to defend the *status quo*, with a zeal that would be difficult to reconcile with modern ideas about technological progress. Pliny, however, after dismissing the story’s credibility, goes on to describe the fantastically expensive Neronian cups, with the clear implication that, if Tiberius wanted to prevent anyone from creating glass objects more valuable than gold, he failed. Resistance to technological change is, to some extent, futile in Pliny’s Empire.

\(^{217}\) Henderson 2013, p. 233.
Conclusion

Julian Henderson characterizes the beginning of the Imperial period as a time in which glassworking was shifting from a fairly conservative craft to a very innovative one. This is perhaps selling short the achievements of Hellenistic glass artisans, who did, after all, beat the Romans to creating the first mass-produced glasses, and showed great artistic creativity in their mosaic glass pieces. However, the rapidity with which the Romans adopt, perfect, and make universal a completely new and revolutionary technique is nothing short of astounding, and the economic impacts of these developments are equally so. Pliny, at least, seems to have been acutely aware of this, though whether he regards these developments as positive is perhaps a more open question, since some of his anecdotes suggest that he may have associated new developments in glass production with an excess of luxuria. In their transformation of the glass industry, we see the Romans at their most “modern.” Techniques spread and evolved rapidly, a specialized craft material became available all over Europe, and what had been a gemstone-like elite product in former periods became cheap and mass-producible. Fine glass had never before been made with such efficiency or such scope for variation, and it would be centuries after the fall of the Empire before it would be again.

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218 Henderson 2013, p. 251.
Section 4: Current Issues in Glass Analysis

This chapter’s focus is the methods and practice of chemical analysis of Roman glass. A brief description, aimed at a non-specialist audience, of the analytical techniques currently and formerly in use in the study of archaeological glass will aim to show the advantages and disadvantages of each, and to give some impression of the earlier history of the field. The limitations of these techniques shape new research, and define the questions we may ask of our evidence. An overview of several important studies on ascertaining the sources of the raw materials of Roman glass will follow. This review will focus on a key question in recent investigations of Roman glass: did primary production of raw glass occur on an economically significant scale in the western half of the Roman Empire (at any period), or was production always dominated by the great Levantine centers that are associated with glassmaking in the literary record?

General Analytical Principles

Before describing the specific techniques in common use today, it seems appropriate to offer some preliminary remarks on the scientific characterization of archaeological materials in general, and on geochemical sourcing in particular. This section will discuss destructive analysis in archaometry, introduce the basic ideas underlying source location studies based on chemical composition, and describe some of the concepts that influence how we interpret data from many different techniques.
In the first place, analysts must bear in mind that the objects we wish to study with archaeometric techniques are often of inherent cultural or artistic importance. Moreover, they may form the basis of future stylistic and typological studies – or, for that matter, future scientific studies using more advanced instrumentation than is currently available.\textsuperscript{219} Artifacts, even the most banal and non-diagnostic, are fundamentally irreplaceable. Therefore, from the perspective of the excavators or curators responsible for these artifacts, the single most important parameter of an experimental technique will often be the amount of damage it causes to the sample. This criterion proved a significant handicap for chemical characterization studies for much of the 20\textsuperscript{th} century. Today, the sample sizes required by destructive techniques continually diminish as technology improves, but it is still generally considered preferable to use non-invasive techniques like X-ray fluorescence, if at all possible. Nonetheless, certain types of information, notably isotope ratios, still cannot be obtained except by destructive analysis of relatively large samples. It is also worth noting here, in passing, that the sample treatments required in destructive analysis of ceramic materials are often quite intensive. Due to the strong chemical resistance of their silica network structures, acid digestion of glass and pottery is regularly quite time-consuming, and requires the use of extremely aggressive reagents such as hydrofluoric acid, making it impractical for use in the field.

The process of sample selection for destructive methods is the subject of worryingly little discussion. In studies of material from a single site, generally intended for incorporation into the site publication, one is generally told that samples were chosen with the aim of providing good representation of everything found at the site (whether

\textsuperscript{219} Galanidou 2006, p. 358.
this is based on a stylistic typology, or on some other criterion like color that seems likely to correlate with compositional features).\textsuperscript{220} In studies that make use of material from multiple sites, one may read that samples were “selected,” but not according to what rationale.\textsuperscript{221} We should bear in mind here that the scientists performing the analyses, and writing the reports, are very often not directly involved with field work; in some cases, they see no more of a site than the finds that are specifically brought to their attention by archaeologists.\textsuperscript{222} The availability of samples will be a function of funding, the decisions of excavation leaders, and local laws on the ownership and treatment of antiquities. These issues can be complicated even when dealing with an artifact type as ubiquitous as pottery; glass, while fairly common at most Roman sites from the 1\textsuperscript{st} century B.C. onward, is usually found in significantly smaller quantities. Even at glassworking sites like Jalame, sherds of pottery can outnumber those of glass.\textsuperscript{223} In many cases, it may be difficult for excavators to pick sherds that they are willing to have drilled for a powder sample, or even digested in their entirety as sometimes happens in isotope studies. It is difficult to expect a fixed percentage of all sherds, or a fixed number from each stratigraphic layer, to be set aside for this kind of treatment, the way we might set aside, say, every tenth or fifteenth bucket of soil for archaeobotanical analysis, but clearly some systematic rationale is necessary. Recognizing these issues, and being explicit about our sample selection processes, especially when submitting samples for destructive analyses, should be entirely standard.

\textsuperscript{220} \textit{e.g.} Brill 1988, p. 257.
\textsuperscript{221} \textit{e.g.} Freestone \textit{et al.} 2003, pp. 22-25.
\textsuperscript{222} Andrews and Doonan 2003, p. 33.
\textsuperscript{223} G. Weinberg 1988.
This becomes all the more important when we remember that sample sizes in archaeometry are rarely what scientists and statisticians would like them to be. Excavators will offer a dozen samples when, from a statistical point of view, a hundred would provide much more secure data. Mike Baxter, Hillary Cool, and Caroline Jackson offer a compelling, and worrying, cautionary tale from their work on colorless Roman glass from Colchester. When they analyzed samples taken from 62 facet-cut beakers, they found consistent compositional traits (high lead and antimony levels, compared to the other colorless vessel types in the study), which, in an earlier study of only 15 of the same beakers, had instead been identified as anomalous features of only a few samples.  

The distinctive composition turned out to be “the rule… rather than the exception” when the sample set was expanded beyond the small size that is itself, unfortunately, the rule rather than the exception in archaeometry. Many archaeologists will admit to difficulty working with quantitative data and statistical analysis, even without the added bewilderment of dealing with unfamiliar techniques from the physical sciences. Attempting to engage with this problem in depth is not possible here, but we should acknowledge and remember from the outset that archaeological science errs more often on the side of too few samples than too many.

When we analyze archaeological materials, we generally seek to identify compositional groups, and relate them to geographical locations, manufacturing technologies, raw materials, or other factors. There is no universal, statistically rigorous definition of what constitutes a compositional “group,” though once a group is defined, statistical tests will discern whether a given sample is a member of it. We

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can think of a “group” simply as a collection of samples, which are, by some objective measurement(s), more similar to each other than they are to samples outside the group. When an analysis measures more than three or four parameters (elements, usually) at once, it becomes extremely difficult to group samples “by eye;” compositional groups are therefore usually defined with the aid of statistical software packages, generally making use of some form of multivariate analysis. At their most basic, these analyses can be thought of as plotting samples in an n-dimensional space, where n is the number of parameters being measured, and calculating their Euclidean distance from each other, as a concise indicator of their similarity.\footnote{\text{Bieber et al. 1976, pp. 63-64.}} Many elaborations on this principle are possible, such as using the ratios of different parameters, or giving greater weight to the parameters that the software judges to be most useful in discriminating groups.

At the broadest level, chemical analysis can identify the kinds of ingredients that were used to produce the glass, and thereby the technological tradition in which its makers were working. As we have seen (see section 2), a typical ancient glass has three main chemical components: silica (SiO$_2$), which makes up the bulk of the glass and provides its physical strength; soda (Na$_2$O), potash (K$_2$O), or both, which act as fluxes; and lime (CaO), which compensates for the harmful effects of the flux on the chemical resistance of the glass. Possible formulations for incorporating these three components include quartz (SiO$_2$) + plant ash (Na$_2$O/K$_2$O and CaO), sand (SiO$_2$ and CaO) + natron (Na$_2$O), and quartz (SiO$_2$) + shell (CaO) + natron (Na$_2$O).\footnote{Brill 1988, p. 265.} Each of these ingredients has a distinctive effect on the overall major element composition of the glass, which can be discerned without any need for statistical analysis. Plant ash
glasses, for example, will include significant (between 1% and 10%) amounts of magnesium oxide (MgO), largely absent from natron glasses; glasses made with sand will often include iron (II) oxide (FeO) and alumina (Al₂O₃) in similar quantities, derived from mineral particles in the sand, while these will not be major components of a glass made from ground quartz. In the same way, intentionally added colorants are typically quite easy to identify on the basis of multiple samples; this was the aim of most analyses of archaeological glass up until the middle of the 20th century. Some colorants, like turquoise copper (II) oxide (CuO), are effective at concentrations of 1-2%; others, like deep blue cobalt oxide (CoO), can produce intense colors at concentrations of 0.1% or less.

Today, the ultimate goal of many, perhaps most, chemical analyses of Roman glass is to determine the locations at which these materials were produced. The basic premise of this kind of work, by analogy with similar studies of pottery, is the idea that artifacts made using the mineral resources of a particular region will bear that region’s geochemical “fingerprint,” a combination of trace elements or isotope ratios that can be considered characteristic of that region. In theory, artifacts of the same type, produced by the same methods, will not share this “fingerprint” if they were made using the resources of a different region. In an ideal scenario, with access to external reference in the form of geochemical survey data, it should be possible to pinpoint the sources of certain raw materials in absolute terms. In practice this is rarely straightforward even when dealing with pottery, as the precise composition of raw materials may be altered by washing or mixing during the production process, though

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228 Caley 1962.
229 For some illustrative examples of success in the application of this principle to pottery, see Grave et al. 2013 and Poblome et al. 2002.
encouraging success stories do exist. It is much easier and more reliable to compare artifacts to each other, grouping them by their chemical signatures. The groups that are most abundant at a site, in particular those whose members are associated with workshops on the site, can provisionally be assigned to local production; anomalous groups, especially those similar to samples from other sites, may represent imported wares.

For glass the question of sourcing is more complicated still, because in pottery, ingredients additional to the base clay (temper, grog, and so on) can, in theory, be identified as inclusions and characterized in isolation by techniques such as scanning electron microscopy. Glass may contain inclusions as well, notably crystalline opacifiers such as calcium antimonate, which can be picked out in the same way. However, the ingredients that make up a glass are mixed together at the molecular level; sodium from natron and calcium from the shell component of sand, along with any trace elements associated with either ingredient, are chemically bonded into the glass’ silica matrix. The same is true of the elements responsible for color (except in the case of opacifiers), though incomplete mixing sometimes results in streaks of more or less intense color that can be characterized separately. The different ingredients come with their own geochemical fingerprints, and these overlap in the composition of the glass. It is impossible to extract these raw ingredients, or characterize them separately; we must take them as they come, as a mixture of unknown proportions. Fortunately, Roman glass seems to have been made using sand and natron, and the latter ingredient is extremely pure by geological standards due to its evaporitic nature, but determining where impurities in a glass are likely to have

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231 e.g. Brill 1988, pp. 275-276.
come from is still an important step in trace element analysis. In order to simplify matters, studies aiming to determine the sources of sand used in glasses tend to focus on uncolored glass, or glasses that are all colored in the same way; the presence of colorants, and impurities associated with them, can have an effect on glass composition that is much more distinctive than sand source.

Before moving on, a brief word on terminology is necessary, specifically on the terms “provenience” and “provenance,” both of which are often used in connection with the kind of work just described. These words are used with disparate meanings by different disciplines. “Provenience,” in archaeology and art history, refers to an artifact’s find spot and archaeological context. “Provenance,” by contrast, refers mainly to its history since its modern discovery; for instance, records of an artifact’s ownership by museums and private collectors form part of its provenance. In archaeometry and geochemistry, however, both terms (though more commonly “provenance”) can be used to refer to the geographical origins of the raw materials that were used to make the object. The location of the clay beds that provided a raw material for a pot, for example, might legitimately be described as that pot’s geological “provenance” or “provenience,” in a usage that is inconsistent with the archaeological definitions of both. Because of their inconsistent usage across disciplines, I have avoided both “provenience” and “provenance” in this review, in favor of less ambiguous phrasing such as “geological source” and, where appropriate, “find spot” or “location of manufacture.”

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232 Brems and Degryse 2014, pp. 117-120.
The majority of the techniques described below are fundamentally forms of elemental analysis, which provide either relative or absolute figures for the abundance of individual elements, not compounds, in a sample. In the case of glass, results are normally reported in terms of the percentage by weight of the different oxides (e.g. SiO$_2$, CaO, Na$_2$O, Al$_2$O$_3$) in the sample, but this is a matter of convention. The raw data, in most cases, includes values for the different metal ions, and the reported data is derived from the known relationships between each of these and the oxygen atoms that make up the bulk of the material’s silica lattice (see section 2). This format does not reflect the state in which the atoms exist in the glass (they form a continuous network, with no discrete molecules), nor what has been conjectured of ancient practice, in which the ingredients in a glass batch may well have been measured by volume.\textsuperscript{233} The use of percentage by weight of oxides does stress the importance of oxygen in the network structure of glasses, but is more a convenient standard than anything else.\textsuperscript{234} It also allows easy comparison, where applicable, with earlier analyses that made their determinations using primarily “wet chemical” methods, physically separating the various components of a powdered sample using a carefully planned series of aqueous-phase reactions, as was common until the middle of the 20\textsuperscript{th} century.\textsuperscript{235}

As with metals, it is important when performing and interpreting chemical analyses to be aware that old and broken glass can be crushed, remelted, and recycled into new glass vessels. Luckily, there is an easy way to identify recycled glass: conspicuous enrichment of a sample in trace elements, particularly the transition metals commonly

\textsuperscript{233} Brill 1988, p. 419.
\textsuperscript{234} Pollard and Heron 1996, pp. 162-163.
\textsuperscript{235} Caley 1962, pp. 24-66; see e.g. Klaproth 1801, the first known study of this kind, and for many decades one of the best.
used as colorants such as copper, cobalt, and manganese, is a telltale sign of colored cullet that was not completely sorted out before re-melting.\textsuperscript{236} The same is true of lead, which seems to have been used to make glass that was easier to carve, and magnesium in natron glass, which can be introduced as a contaminant from fuel ash. It can be generally assumed that glass in large chunks, the form in which raw glass seems to have been sold to glassblowers in antiquity, has not been recycled.\textsuperscript{237} The experience of multiple studies shows us that recycling was common in classical antiquity, though much less so than in the early Mediaeval period.\textsuperscript{238} Even the identification of glass as recycled does not render analytical data useless, though it does demand greater caution in interpretation.

Both recycling and the mixed nature of glass composition can be dealt with in interpretation of elemental analyses using similar methods; namely, we can look at the relationships between two or more elements. If there is a statistically strong correlation between the abundance of two elements that holds true across a large group of samples, it is likely that those elements entered the glass mixture primarily or exclusively from a single source, whether that source was a naturally occurring material or recycled cullet. A basic example is the widely observed correlation between copper, tin, and lead in Greek and Roman blue or green glasses, and indeed in other copper-bearing synthetic materials such as Egyptian Blue pigment. This correlation suggests that the copper-bearing ingredient in the production process was bronze (which in classical antiquity normally contained lead), probably scrap

\textsuperscript{236} Freestone et al. 2002, p. 271.
\textsuperscript{237} Freestone et al. 2003 p. 22.
\textsuperscript{238} Degryse and Schneider 2008, p. 1994.
metal. A facile conclusion, one might think, but other perfectly viable alternatives would have been available to ancient glassmakers, including both pure copper and copper-bearing minerals such as malachite, which would not have introduced appreciable quantities of tin. A strong negative correlation between two elements, conversely, can sometimes indicate the mixing of two types of recycled glass.

Some of the techniques described below will determine the chemical composition of an entire sample; others, notably X-ray fluorescence, which is extremely popular because of its non-invasive nature, characterize only the surface of the sample. These techniques may not give wholly representative results if the sample’s composition differs between the surface and the bulk due to the effects of corrosion. We can again draw comparisons to the characterization of metal objects, where the formation of oxide, carbonate, or chloride layers (e.g. the characteristic green patina of old bronze) results in the surface composition potentially varying significantly from the bulk composition. The chemical processes that take place in glass are very different, involving mainly the leaching of alkali metals from the silica matrix by exposure to water (see section 2), but the practical effect is similar. Surface-only characterization is not necessarily a disadvantage for a technique, as a comparison between surface data and bulk measurements taken by another technique can potentially yield interesting information about corrosion processes. However, it should be borne in mind as a limitation if only surface characterization techniques are in use; in this case, it may be necessary to abrade corroded layers from a sample before analysis, or take a powdered sample (sacrificing the non-invasive quality of X-ray fluorescence).

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239 Fiori et al. 2004, p. 75.
240 O’Hea 2013, p. 16.
241 Goffer 2007, pp. 188-197.
Analytical Techniques

Most of the techniques in common use today for chemical analysis of archaeological glass are forms of spectroscopy. The fundamental principle that these techniques have in common is that atoms and their electrons can transition between stable, low-energy “ground states” and unstable, high-energy “excited states” by absorbing and emitting photons of specific, predictable wavelengths, which are characteristic of particular elements or compounds. The wavelength ($\lambda$) of a photon is inversely proportional to the energy ($e$) it carries, according to the equation $e = hc/\lambda$ (where $c$ is the speed of light in a vacuum, and $h$ is Planck’s constant). A transition between two energy levels is associated with the absorption or emission of a photon whose energy corresponds exactly to the difference between the two levels. Therefore, if we can identify and quantify the absorptions that take place when light is transmitted through a sample, or the emissions when a sample is energized by heat or electricity, we can ascertain aspects of its chemical composition.

The most conceptually straightforward forms of spectroscopy we will encounter here are the atomic techniques, atomic absorption and atomic emission spectroscopy (AAS and AES). As the names imply, atomic absorption and atomic emission spectroscopy both require that samples be atomized (molecules will show different absorption and emission spectra, usually much blurrier). There are a variety of ways to do this, usually dictated by the nature of the material under study; most common is acid digestion, followed by aspiration in a flame or incineration in a graphite furnace.

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Because the sample is atomized, the data will reflect the abundance of each element in numerical terms; it will tell us nothing about factors relating to the chemical environment of atoms, such as the oxidation states of transition metals in the glass, or the nature of any inclusions.

In AAS, a beam of light at a carefully controlled wavelength, corresponding to a major electronic transition of one of the elements being measured, is fired through the flame or furnace chamber. A detector then measures the reduction in the light’s intensity due to absorption by atoms in the flame. The lower the intensity of the transmitted light is, the greater the number of atoms in the beam’s path that are capable of absorbing at the selected wavelength; the relationship is a linear one, and deriving concentration from transmittance is a simple matter.243 Because the light source needs to be selected and calibrated, AAS will only measure elements that are specified in advance.244 For the same reason, it will sometimes be able to measure only one element at a time, with time-consuming lamp changes in between (in modern instrumentation, these are of course automated, but the time taken is still significant when large numbers of samples are being measured).

AES is, in a sense, the reverse of AAS: it measures light given off by atoms returning to the ground state after being excited by the energy of the flame. It is simpler to perform, needing no special light source, and can therefore measure a more comprehensive spectrum. However, because the technique measures the relaxation of

243 The relationship between absorption (A) and the concentration of the absorbing species (c) is expressed by the Beer-Lambert equation, $A = \varepsilon bc$, where $b$ is the distance the light travels through the absorbing medium, and $\varepsilon$ is the molar absorptivity, a constant that is specific to a given analyte at a given wavelength, representing the probability that an atom will absorb a photon.

244 Pollard and Heron 1996, pp. 29-30.
excited atoms, which are fewer in number than atoms in the ground state, its sensitivity and detection limit suffer significantly in comparison, and it will generally require a hotter flame than AAS.\(^{245}\) Signals can also be “quenched” at high analyte concentrations if ground state atoms re-absorb the photons emitted by excited atoms.\(^{246}\) Modern instrumentation for AES can alleviate these disadvantages to an extent by the use of inductively-coupled plasma (ICP, which will be described in more detail in connection with mass spectrometry), as the extremely high temperature of the ICP flame increases the population of excited atoms, and the evenness of its temperature reduces the impact of quenching.\(^{247}\)

Both AAS and AES require a relatively large sample, which is destroyed. As a result, their use in archaeological applications is declining in the 21\(^{st}\) century, in favor of more specialized non-destructive techniques like XRF and EDX (see below), which provide a similar kind of data – a profile of a sample’s elemental composition. However, they occur with some regularity in slightly older studies of glass and pottery, and are far from obsolete; AES in particular is often used today as a complement to other techniques.\(^{248}\) As a result of their continued popularity in other applications of analytical chemistry (where the loss of a sample is often not a major sacrifice), the relevant technology continues to improve steadily, with excellent accuracy and precision possible on modern instrumentation. In addition, most

\(^{245}\) Pollard and Heron 1996, pp. 30-31.
\(^{246}\) Harris 2007, p. 396.
\(^{247}\) Harris 2007, p. 468.
\(^{248}\) Sayre and Smith 1961 employed early forms of the atomic emission technique; see also Frank 1972, pp. 49-50 for additional early examples; Jackson et al. 2003 and Freestone et al. 2003 for more recent applications with atomization by inductively coupled plasma (ICP).
analytical laboratories will own instruments, making these techniques among the cheapest and most accessible of those described here.

Possibly the most common technique in the elemental analysis of archaeological glass today is scanning electron microscopy (SEM). SEM, like the more familiar optical microscopy, is essentially an imaging technique; it is capable of producing images at a magnification factor in the hundreds of thousands, far superior to any optical microscope. What makes it useful for chemical analysis is the way in which these images are created, and the additional information that can be extracted from them by coupling SEM with appropriate detection methods, most commonly energy-dispersive X-ray spectroscopy (EDX or EDS). An electron microscope works by firing a beam of electrons at the surface of a sample (under high vacuum conditions, so that the beam will not be disrupted by gas molecules). During this process, low-energy electrons of atoms in the sample impacted by the beam are often knocked out of their orbitals. In order for these atoms to return to their ground state, electrons in higher-energy orbitals must drop to a lower energy level to fill the “hole,” by releasing excess energy as an X-ray photon. Relief images of the surface can be built up by detecting either emitted X-rays or electrons sputtering off the surface.

The second component of the analysis involves measuring the precise energy of the X-ray emissions, which are characteristic of particular electronic transitions in the elements that released them, in the same way as the emissions recorded in AES. Unlike in atomic spectroscopy, the relationship between signal strength and the abundance of an element in the sample is not precisely linear, because the probability

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249 Shortland 2012, p. 179.
of any given electronic transition is influenced by the presence of neighboring atoms.\textsuperscript{250} However, proprietary software capable of disentangling these relationships and producing a quantitative read-out of a sample’s elemental composition is readily available. With slightly different instrumentation, it is alternatively possible to analyze the X-rays emitted during scanning electron microscopy by their wavelength (by measuring the angles at which they are diffracted through several crystals) rather than by their energy.\textsuperscript{251} The resulting technique is SEM-WDX (wavelength-dispersive X-ray) microprobe analysis.

Both forms of SEM can only take measurements at the surface of a sample, and can therefore be stymied be corrosion effects as described above. However, in the case of SEM, this disadvantage is counterbalanced by the fact that the electron beam is finely targetable. Measurements are taken at discrete points, and scanning across the sample’s surface can build up a picture of compositional variation within the object. In a glass sample, for instance, the crystalline inclusions that give rise to opaque colors can be targeted and characterized separately from the glass matrix.\textsuperscript{252} Taking full advantage of this ability can make SEM-EDX a very powerful technique indeed.

SEM-EDX is cheap, widely available and relatively straightforward to use; however it is not without disadvantages. Because SEM requires that the sample be placed in a vacuum chamber, it can rarely be used for the analysis of whole artifacts; samples must be broken off (small sherds, however, are often ideal).\textsuperscript{253} Moreover, standard

\textsuperscript{250} Shortland 2012, p. 179.
\textsuperscript{251} Janssens 2013, p. 130.
\textsuperscript{252} e.g. the characterization of lead antimonate and calcium antimonate inclusions in Arletti et al. 2006, pp. 178-179.
\textsuperscript{253} Shortland 2012, p. 180.
procedure requires that items be coated in a conductive material such as graphite, so
that charge build-up caused by the electron beam will not ruin the analysis. For many
archaeological samples, this will obviously be undesirable. EDX also has relatively
low detection limits, on the order of 0.1% (contrast the detection limits in parts per
billion achievable in certain forms of mass spectrometry), and generally poor
resolution in comparison to atomic spectroscopy, which can make it difficult to
distinguish between elements whose major transitions occur at similar energies. To
take an example relevant to glass chemistry, the iron Kβ transition at 7.06 keV can
interfere with detection of the cobalt Kα transition at 6.93 keV (the designations Kβ
and Kα refer to the particular atomic orbitals involved in the transition). This latter
disadvantage can sometimes be obviated, since any given element has multiple
possible electronic transitions, each with its own characteristic energy; we can simply
measure a transition that does not conflict. In the above example, one could instead
measure the iron Kα transition at 6.40 keV. However, this will not always be possible
as less common transitions may be drowned by instrumental noise. SEM-WDX
experiments escape these problems because the microprobe only detects one
wavelength (and therefore one transition) at a time, physically moving the detector to
identify different wavelengths produced by different elements. However, this also
means that WDX experiments are much slower and will only collect data for the
transitions specified in advance, while EDX will measure a full spectrum (cf. the
relative merits of AAS and AES).

Another very popular technique today, in the study of archaeological and heritage materials of almost all kinds, is X-ray fluorescence spectroscopy (XRF). This technique functions in a similar manner to EDX, except that instead of measuring X-rays whose emission is prompted by electron bombardment, it uses X-rays as the initial exciting stimulus, and measures fluorescence, the delayed emission of a photon of lesser energy (i.e. longer wavelength) than the incident X-ray (see figure 4.1). X-ray fluorescence possesses many conspicuous advantages for archaeologists. As X-rays are not so easily disrupted as electron beams, the technique requires no vacuum chamber, and it has therefore been possible for some time now to design low-power portable XRF scanners, which can be used in the field.\textsuperscript{256} These have been most enthusiastically adopted for pigment analysis, being incredibly useful for studying delicate \textit{in situ} wall paintings. XRF is also non-destructive and generally has low detection limits. A disadvantage of this technique as compared to EDX is that the irradiation is less finely targetable than an electron beam; therefore, it cannot usually characterize inclusions or decorative \begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure41.png}
\caption{The basic process of XRF. After Janssens 2013, p. 83.}
\end{figure}

\textsuperscript{256} Janssens 2013, p. 89.
features separately from the bulk, or provide the high-resolution imaging capability of an electron microscope.\textsuperscript{257} Furthermore, like EDX, it characterizes only the surface of a sample, and can give misleading results if the material is not homogeneous.

All of the techniques described above work, ultimately, by exploiting the same fundamental rules that govern the interaction between light and matter. We move now to a very different class of technique: mass spectrometry, where the mass of particles themselves is the property of interest. A mass spectrometer has two main components: an ion source and a mass analyzer. The function of the ion source is to reduce a sample to a stream of gaseous charged particles; these can be broadly divided into “soft” ion sources, which tend to ionize whole molecules or large fragments of molecules, and “hard” ion sources, which are more likely to reduce molecules to monoatomic ions (these should be distinguished from the \textit{uncharged} free atoms we study in AAS and AES).\textsuperscript{258} The choice of ion source will depend on the material being analyzed. The function of the mass analyzer is to sort positively charged ions by mass (or, more accurately, by mass-to-charge ratio) by using magnetic fields to influence the paths they take to a detector. Lighter particles will be deflected to a greater extent than heavier ones; different mass analyzers exploit this basic concept in different ways. Many types of both components exist. Today, glass and pottery are most commonly analyzed using an inductively-coupled plasma (ICP) ion source coupled with a quadrupole mass analyzer, which is the current industry standard in many commercial applications of analytical chemistry.

\textsuperscript{257} Janssens 2013, p. 80.
\textsuperscript{258} Harris 2007, pp. 474-496.
The finer details of the functioning of the mass analyzer are likely to be of tangential interest at best to most archaeologists, but the nature of the ion source is important as it has an impact on sample preparation and on the types of interferences that can occur. Soft ion sources are used for studying organics, and in archaeology are most commonly associated with residue analysis; these can allow us to glean information about the structure of complex organic compounds (like those that impart flavor to food and drink, or scent to perfumes) by analyzing the patterns of large and small fragments they produce when ionized. In glass studies, however, we are looking for the elemental composition of a sample, and for this purpose a hard ion source, such as ICP, is more appropriate. An ICP torch, which can also be used in connection with AES, is built around a stream of carrier gas, usually argon because of its inertness, which is initially ionized by a spark and forced into a toroidal flow by an induced magnetic field. The charged particles’ resistance to this flow creates extremely high temperatures, normally in excess of 5000 ºC, which prompt atomization and ionization of the sample when it is introduced to the carrier stream. Samples must be introduced to the plasma stream in an already rarefied form. Acid digestion is one common method of sample preparation for ICP, but its destructive nature and its inefficiency in dealing with glass and pottery make it suboptimal for our purposes. As a result, archaeometrists today generally prefer the laser ablation method, whereby a minimal amount of material is blasted from the surface of the sample using a laser, then swept along in the argon stream. As with SEM-EDX, it should be noted that ICP-MS, if laser ablation is used in preference to acid digestion, will only characterize the surface of a sample, which will not always be representative of the bulk.

Fassel 1978, 184-185.
Shortland 2012, 186.
e.g. Shortland and Schroeder 2009, Baxter et al. 2005.
Just as spectroscopic techniques can be confused by elements whose characteristic absorptions and emissions have similar energies, a mass spectrometer suffers when confronted with ions of very similar masses. A particularly prominent source of such “isobaric” interference in ICP-MS is argon, since it is abundant in the plasma stream. The most common isotopes of argon and calcium have the same atomic mass, 40. In addition, although argon does not normally react with other elements, the extreme conditions of the high-temperature plasma stream can cause it to behave atypically and form diatomic ions such as ArO⁺, which has a mass of 56, the same as the most common isotope of iron. Both iron and calcium are important elements in the classification of glass samples, calcium oxide being one of the principal components of soda-lime glass, and iron (II) oxide one of the most common and abundant impurities. It is usually possible to “work around” isobaric interferences by measuring less common stable isotopes that occur in a predictable and well-known ratio to the major isotopes (⁴⁴Ca instead of ⁴⁰Ca, for instance). However, as the signals of these isotopes will, of course, be much weaker, this is an imperfect solution.

Because mass spectrometry sorts the components of a sample by mass, it is able to quantify isotopes of a single element. Isotopes are interchangeable for the purposes of the vast majority of chemical reactions, but will be unevenly partitioned by many physical processes, such as evaporation and precipitation, due to their differing

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²⁶² In fact the exact masses are subtly different – ⁵⁶Fe⁺ actually has a mass of 55.9349, while ⁴⁰Ar¹⁶O⁺ has a mass of 55.9573 – and some instruments can reliably distinguish the two signals, however the superior resolution often comes with trade-offs in other parameters, such as sensitivity and detection limit. The atomic masses of ⁴⁰Ar and ⁴⁰Ca differ at the fourth decimal place, and can only be resolved by extremely powerful – and expensive – instrumentation.
masses. Some are also unstable, and their relative abundance in a closed system will diminish over time due to radioactive decay. This latter process is what enables the best-known, and probably the most impactful, application of mass spectrometry in archaeology; radiocarbon dating, where the isotopes of interest are stable \(^{12}\)C and unstable \(^{14}\)C. The same analytical principle can be applied to other elements or isotopes for several purposes; for example, the ratio of \(^{12}\)C to \(^{13}\)C, in conjunction with that of \(^{14}\)N to \(^{15}\)N (all four of these isotopes are stable), can be used to extract dietary information from bone collagen samples.\(^{263}\) Isotope ratios of heavier elements like lead are most commonly investigated with a view to determining the sources of raw materials, which relies on the idea that isotope ratios in minerals exhibit geographical variation that is well characterized, and will not have changed measurably over the last 2000 years. This kind of variation often arises because some isotopes are “radiogenic”; they can be formed as the decay products of heavier radioactive elements, but are themselves stable. Their abundance relative to other isotopes of the same element is therefore dependent on the age of the rock (indeed, radiogenic isotopes are commonly used in geology to date rocks), and the amounts of their parent isotopes that were present in the rock when it was formed. Isotopes of light elements, on the other hand, exhibit variation because the large relative difference in their atomic masses (\textit{e.g.} \(^{18}\)O is 12.5\% heavier than \(^{16}\)O, while \(^{206}\)Pb is only 1\% heavier than \(^{204}\)Pb) causes them to be easily fractionated by physical processes. For example, water molecules containing \(^{18}\)O evaporate significantly less readily than those containing \(^{16}\)O, and precipitate significantly more readily, so that water in clouds contains less \(^{18}\)O than water in the oceans. Geographical variation is thus driven by phenomena such as the history of global temperature fluctuations.

\(^{263}\) \textit{e.g.} Buikstra and Lagia 2009, pp. 17-19.
Isotopic studies focus on a single element. The absolute concentration of the element in a sample is usually not of interest; we are concerned only with the concentration of its different isotopes relative to one another, and how these ratios vary from the global averages defined in the literature. As such, it is normal to reduce interferences by isolating the element of interest from a powdered sample using acid digestion and chromatography, making the majority of these methods destructive.\textsuperscript{264} The sample sizes required are relatively large, on the order of 0.1-1 grams of powder; sample preparation procedures will sometimes grind an entire sherd.\textsuperscript{265} Isotope studies also tend to be among the more expensive of the analytical procedures described here. As a result, despite their potential usefulness, they are not generally a part of standard excavation procedure. However, several specific elements have important places in our understanding of the structure of ancient glass production industries, and these deserve to be described individually. They include oxygen, lead, strontium, neodymium, and boron.

The most famous use of oxygen isotopes is in taking measurements from layers of glacial ice cores in order to estimate past global temperatures, but geological variations in oxygen isotope ratios can also contribute to questions of raw material source locations. Brill investigated these possibilities in his work on the Roman glasses of Jalame, though with limited success.\textsuperscript{266} Oxygen is present in all the major components of most glass mixtures, so it is difficult to use oxygen isotopes alone to derive the geological source of any one raw material, though they can help to

\textsuperscript{264} \textit{e.g.} Devulder \textit{et al.} 2013; Degryse and Schneider 2008.
\textsuperscript{265} Shortland 2006, pp. 188-194.
\textsuperscript{266} Brill 1988, pp. 288-291.
corroborate a hypothesis based on other data. For typical Roman glasses made from sand and natron, oxygen isotope analysis is more a novelty than anything else; however, in other regions and periods, it can be extremely effective at distinguishing between types of geological silica sources – quartz and chert, for example.  

Lead has four major stable isotopes, \(^{204}\text{Pb},^{206}\text{Pb},^{207}\text{Pb},\) and \(^{208}\text{Pb},\) of which the final three are radiogenic; it therefore exhibits significant geological variation in its isotope ratios. Lead isotope analysis has been used on these grounds to source pigments in Roman fresco that contain significant amounts of lead as an impurity, such as red cinnabar. Roman glass primarily derives lead from certain colorants, most notably copper blue (since Roman bronze normally contains large amounts of lead), lead antimonate yellow, and decolorizing antimony ore (which is often geologically associated with lead); in glass studies, lead isotopes are thus mainly useful for determining the geological origins of these ingredients. Here we must use caution in interpreting the results of analyses, as colorants could easily have been added either to an initial batch of raw glass, or to a batch remelted in a secondary workshop for use in the production of vessels. It is therefore not necessarily self-evident whether lead isotopes reflect the geology of the region of primary or secondary production. It has been argued that glasses with low lead concentrations, not likely to be the result of deliberate coloring, retain the lead isotope compositions of impurities in the sand used to make them.

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268 e.g. Mazzochin et al. 2008.
270 Wedepohl and Baumann 2000, p. 131.
Strontium has been used quite extensively in recent studies of Roman glass, notably in the work of Ian Freestone, focusing on $^{86}$Sr and radiogenic $^{87}$Sr. Strontium enters glass primarily with the calcium source, as it is chemically analogous to calcium and can substitute for it in many minerals and biological processes. Specifically, strontium occurs naturally in the calciferous shells of marine mollusks, in a predictable ratio to calcium, and ultimately finds its way, in much smaller amounts, into limestone, which is formed from crushed fragments of these shells. Strontium has an extremely long residence time in seawater, with the result that stable equilibria form easily between different regions. Geographical variation is thus negligible in both the trace strontium levels and the strontium isotope ratios of marine calcium carbonate. Only variation on a geological timescale is significant. Calcium carbonate in shell, and thus in most sands, therefore has the strontium isotope signature of modern seawater, while calcium carbonate in limestone has the signature of seawater from the geological epoch in which the stone was formed; the history of this fluctuation is well established. In theory, then, if a glass sample has a ratio of $^{86}$Sr to $^{87}$Sr matching that of modern seawater, and a relatively high ratio of strontium to calcium (on the order of 1000-2000 parts per million), then its calcium source was probably crushed shell. If it has an anomalous isotope ratio and a low strontium content, then the calcium source is more likely to have been crushed limestone. Furthermore, in the case of limestone, it should be possible to determine the age of the original deposit and therefore a range of possible geographic origins. With regard to the study of regions and periods where ash glasses were the norm, we should also

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271 Wedepohl and Baumann 2000, p. 130.
272 Freestone et al. 2003.
273 Most relevant for our purposes is a significant rise in levels of strontium-87 over the last forty million years, largely due to the uplift of the Himalayas and the resulting run-off of $^{87}$Sr-rich sediment into the ocean in rivers.
274 Freestone et al. 2003, p. 21.
note that plant ash will match the strontium isotope composition of the region in which the plant grew (the same principle underlies the use of strontium isotope studies in the analysis of teeth and bones, with which many archaeologists will be familiar).

Neodymium has several common stable isotopes. The ones of greatest interest in archaeological glass studies are \(^{143}\text{Nd}\) and \(^{144}\text{Nd}\), of which the former is radiogenic; the geographical variation in their relative abundance is well documented. Like most heavy metals, neodymium occurs in only negligible quantities in natron; glass should therefore retain the neodymium isotope signature of the sand used to make it.\(^{275}\) Particularly fortuitously for our purposes, the isotope ratios of neodymium present in the sediments of the eastern and western Mediterranean are measurably distinct, largely due to the influence of the Nile river, and the unusual East African volcanic sediment it carries, on the geology of the eastern regions.\(^{276}\) These sediments are significantly lower in \(^{144}\text{Nd}\) and higher in \(^{143}\text{Nd}\) than those of the Mediterranean coasts of Spain, France, and Italy, which are dominated by the signature of windblown sediments from the Sahara. Neodymium isotope analysis, therefore, can give a broad indication of whether glass was made from “eastern” or “western” sand; recent work in this area, particularly by Patrick Degryse, is of great importance to our current understanding of the Roman primary glass industry (see below).

Finally, boron has two common stable isotopes, \(^{10}\text{B}\) and \(^{11}\text{B}\). Like oxygen, boron is a light element, and therefore its geographical variation is derived originally from fractionation in physical processes like evaporation. Boron isotope research in

\(^{275}\) Brems et al. 2013b, p. 451.
Roman glass studies is a very recent development, but a promising one. Boron is one of the only elements in a natron glass, aside from sodium, that is derived mainly (though not exclusively) from the flux. Furthermore, experimental evidence shows that the physical processes involved in glassmaking are not likely to cause significant fractionation of boron isotopes. Boron isotope analysis therefore offers a way to confirm the geological source of the natron used in Roman glass – at present, the only way, since the purity of natron compared to most sands makes trace element analysis all but hopeless. Fortunately, Wadi Natrun and the other Egyptian dry lakes have a very distinctive boron isotope signature, skewed very strongly towards $^{11}$B in comparison to the global average. As we shall see, the first steps that have been taken in this area are important ones, though more work still needs to be done identifying and characterizing other potential sources of natron.

Moving on from mass spectroscopy and isotopes, we come to neutron activation analysis (NAA). This was once the unquestionable premier method for the elemental analysis of all manner of inorganic archaeological materials, but particularly pottery, beginning with a seminal 1957 article by Edward Sayre and Richard Dodson that demonstrated the usefulness of the technique in sourcing raw materials. Today it has largely been superseded by newer and more accessible techniques, but still enjoys some favor in analyses of inorganic materials as it can give high-sensitivity, high-precision determinations for a very large number of elements at once. In NAA, a sample is irradiated by bombardment with neutrons, leading to the creation of

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277 Devulder et al. 2014.
278 Devulder et al. 2014, p. 110.
280 Sayre and Dodson 1957.
281 e.g. Freestone et al. 2003, p. 25; Brems and Degryse 2014, p. 122.
unstable radioisotopes with atypical numbers of neutrons. The radioactive atoms in the sample gradually revert to stable forms according to predictable decay pathways, emitting gamma rays whose wavelengths and energies are characteristic of the elements that release them (see figure 4.2). NAA is unique among the techniques discussed here in being potentially able to provide bulk (as opposed to surface) measurements without causing any physical damage to the sample, since both the initial neutron bombardment and the subsequent gamma ray emissions can pass through most solid matter with ease.

![Diagram of neutron activation analysis](image)

**Figure 4.2:** The basic process underlying neutron activation analysis. In usual practice, the delayed gamma rays are the main source of information about the sample’s composition. After Glascock 2013, p. 186.

The technique’s long-standing popularity stemmed from its minimal sample preparation requirements, its ability to measure a large number of elements simultaneously, and the fact that it can, in principle, be performed in a non-destructive fashion, though in practice this is not always efficient. Handling a freshly irradiated sample is, for obvious reasons, highly inadvisable, and it may take months or years for the object to “cool down” to safe levels of radioactivity; accordingly, it is common to measure small (less than 0.1 grams) powdered samples to avoid the inconvenience of handling and storing an irradiated artifact. However, some artifact types, such as
coins, are often analyzed whole, and in these cases NAA can be considered non-destructive.\(^2\) Another important feature of NAA, advantageous for some purposes but detrimental for others, is that it is blind to many of the lighter elements, because they do not easily form radioisotopes. This eliminates the “uninteresting” elements, which make up the largely invariant bulk of many materials, as sources of interference (in the case of glass, this mainly applies to silicon, calcium, and oxygen).\(^3\) The technique’s plainest downside is that it requires access to a neutron source, and by far the most effective of these are certain configurations of nuclear reactors. This will often be an unrealistic proposition. In addition, while the actual procedures of NAA are not particularly time-consuming, measurements are not normally taken immediately after irradiation. Measurements taken immediately will be dominated by the signatures of isotopes with half-lives of hours or minutes; the waiting time is necessary to obtain reliable figures for longer-lived isotopes, whose signals would have been drowned out in earlier measurements.\(^4\) The chosen waiting time will depend on the elements of interest, and may extend to several weeks.

The final two techniques to be discussed here are rarely used in studies of archaeological glass, but are worth brief comment for their specific applications. The first of these is X-ray powder diffraction (XRD). This technique works by illuminating a powdered sample with an X-ray beam, measuring the geometric patterns created by diffraction of the beam as it passes through, and comparing these a database of diffraction patterns. Its main virtue is its ability to determine the crystal structures present in samples, thus differentiating between chemically identical

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\(^3\) Glascock 2013, p. 194.
\(^4\) Pollard and Heron 1996, p. 59.
substances with different crystalline forms (for instance, calcite and aragonite, both forms of CaCO₃, the former prevalent in limestone, the latter in seashells). This can be extremely useful in mineralogy, technological studies of pottery (where the presence or absence of certain crystal structures can be indicative of firing temperature), and pigment analysis, but glass by definition normally lacks any crystal structure for XRD to analyze. Amorphous solids like glass diffract light unpredictably (if they do at all), and produce only low-level background “noise” when subjected to this technique. Moreover, the technique is destructive and, barring access to exceptionally powerful instruments, normally requires relatively large sample sizes. In some cases, however, XRD can be useful for its ability to characterize crystalline phases existing within a glass matrix, particularly opacifying agents such as white calcium antimonate and yellow lead antimonate. Crystalline products of devitrification may also potentially be of interest, as may partially-melted raw materials, which are important as they provide the most secure possible evidence for primary production of glass.

Viscosity-temperature experiments, again, are seldom performed on archaeological glass. These methods are necessarily destructive, essentially involving the re-melting of a fairly large sample of the glass in order to measure its mechanical response to shear forces over a wide temperature range. The result of such an experiment is a viscosity-temperature curve, a description of how the glass becomes more fluid with increasing temperature. Occasional viscosity-temperature studies of non-diagnostic fragments and cullet are perhaps justified, despite their destructive nature, as they...
provide invaluable information on the probable working temperature of glasses. It is practical to work glass when its viscosity is on the order of $10^4$ poise, which for a typical modern soda-lime glass corresponds to a temperature of about 1100 °C.\textsuperscript{289} Annealing can be done at about $10^{13}$ poise (almost completely solid), or a temperature a little above 500 °C. Viscosity-temperature studies formed a part of Robert Brill’s comprehensive campaign of analyses on the Roman glass worked at Jalame, and revealed that most of the important viscosity ranges occur at similar, perhaps slightly lower, temperatures to those for modern soda-lime glass.\textsuperscript{290} Given the strong compositional homogeneity of Roman glasses with respect to their major oxides, we should not expect significant variability in their viscosity-temperature curves. Brill’s results from Jalame are in all probability a good estimate for the properties of almost any typical Roman-era soda-lime glass. If and when more information surfaces about major compositional groups of Roman glass produced outside the core regions, further analyses of this kind might identify technological differences between the traditions, but for now they should not be considered a priority.

The tools available to us in characterizing archaeological glass represent an array that is at times somewhat bewildering. However, only by understanding them, on at least the basic level presented here, can archaeologists hope to become informed “consumers” of analytical services. No one technique can be regarded as a “magic bullet;” each has its conspicuous advantages, whether these are superior analytical precision and accuracy, ability to characterize inclusions and fine detail, limited damage to the artifact, or ability to access highly specific kinds of information.

\textsuperscript{289} Le Bourhis 2014, pp. 85-88. The corresponding temperature for pure silica is well over 2000 °C, which should make it clear why a flux is necessary.\textsuperscript{290} Brill 1988, pp. 280-281.
Portable XRF is beloved by modern archaeologists for its efficiency and non-invasive nature, but perhaps its greatest potential lies in selecting representative or interesting samples for further tests, which are impractical for comprehensive use but provide more specific or detailed information. In order for this kind of strategy to bear fruit, however, archaeologists must be open to engaging with the results of preliminary tests, and allowing those results to inform their choices with regard to future analyses. Ideally, excavation teams need to include staff whose familiarity with the relevant geochemistry – and, ideally, its relationship to issues of archaeological relevance – is more than superficial.

**Issues in the Geochemical Sourcing of Roman Glass**

When we perform chemical analyses of archaeological artifacts, we can extract information about the raw materials from which they were made, and hopefully identify their geological origins. In the case of pottery, this is most often likely to be a clay bed near the potter’s workshop, but geographical associations are not so straightforward when dealing with glass because of the two-step production process that seems to have been the norm in the Roman world (see figure 4.3). There is a

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Figure 4.3: Model of the probable structure of the Roman glass industry from a geochemical perspective. A small number of primary glass factories use a common natron source and their own regional sands to produce raw glass, which is distributed to multiple secondary workshops. After Freestone *et al.* 2002, p. 259.
primary manufacturing step, in which glass is made in large blocks from (usually) sand and natron, and a secondary manufacturing step, in which chunks of glass are softened or melted by artisans for use in the creation of artifacts. These two steps could potentially take place in completely different regions, with chunks of raw glass shipped over great distances in the interim; only in the last twenty or thirty years has this become widely acknowledged in archaeological glass studies. It is very difficult to assign glass vessels to glass workshops in the region in which they were found using chemical evidence; production at this level is investigated mainly through typological evidence, and by studying the archaeological remains of secondary workshops, which are fortunately rather plentiful. The chemical evidence tells us mainly about the primary level of production, and here we are presented with a curious puzzle: namely, that much of it suggests primary production of glass was all but exclusive to the Levant and Egypt in the Roman period. The remainder of this chapter will survey the chemical evidence for the raw materials used in primary production of Roman glass, and discuss some of the problems in interpreting this evidence.

Securely identifying archaeological evidence for primary production of glass is often extremely difficult. A primary glass production site should, of course, have a great deal of waste glass (drippings, slags, and so on) but the same is true of a secondary workshop using recycled vessel glass or imported ingots. Besides the sheer scale of Roman-era primary facilities, the only sure way to identify a primary production site is by the presence of unreacted or partially-reacted batch materials in association with furnace fragments; for instance, quartz sand that has been partially transformed

292 Henderson 2013, p. 18; Foy et al. 2000a, p. 51.
into tridymite or cristobalite (other crystalline forms of SiO$_2$) by exposure to extreme heat. This being the case, securely attested primary glass sites are extremely rare in the Roman period, and almost all of them are in Egypt and the Levant. Tank furnaces for large-scale production are known at Beirut, and were probably active in the 1$^{st}$ century B.C. and early 1$^{st}$ century A.D.\textsuperscript{293} An eight ton unworked slab of badly devitrified purple glass (probably the result of a mistake in the proportions of the ingredients) from a disused cemetery at Bet She’arim, in northern Israel, can only be the product of a similar installation, though only the limestone floor of that tank is preserved.\textsuperscript{294} Its date is uncertain, but no earlier than the 4$^{th}$ century A.D., and possibly as late as the 9$^{th}$\textsuperscript{295} In Egypt, we have three sites where raw glass was probably made in large furnaces during the early Imperial period; two of these, unsurprisingly, are in the area of Wadi Natrun itself.\textsuperscript{296} At Sagalassos in southwest Turkey, where secondary production is well attested, some slags analyzed by XRF, EDX, and XRD appear to suggest small-scale (possibly experimental) primary fusion of an unusual low-calcium, high-aluminum glass from imported sand rich in the mineral nepheline.\textsuperscript{297} However, samples of chunk and vessel glass from the site are of essentially typical Roman compositions, bearing none of the striking chemical traits of the slag samples. Their meaning is thus unclear. All other evidence for primary production up to the 5$^{th}$ century A.D. is either dubious, suggestive of small-scale production only, or both.

\textsuperscript{293} Kowatli \textit{et al.} 2008, pp. 103-120.
\textsuperscript{294} Brill 1967.
\textsuperscript{295} Gorin-Rosen 2000, p. 55. The latter date is derived from chemical analyses by Brill that appear to be more consistent with Islamic than with Roman glass.
\textsuperscript{296} Nenna \textit{et al.} 2000, pp. 99-103.
\textsuperscript{297} Degryse and Poblome 2002, pp. 351-352.
In the western Empire, we have very little. Four tank furnaces at Autun, in eastern France, dating to the late 2nd and early 3rd centuries A.D., are confidently assigned to primary production by the excavator, Alain Rebourg.\textsuperscript{298} However, they are small in comparison to their Levantine and Egyptian counterparts at 1.9 \times 0.88 meters (compare the Bet She’arim slab, a massive 3.4 \times 1.94 m; the Beirut furnaces operated on a similar scale), and it is possible that they were used only for recycling broken glass.\textsuperscript{299} Traces of batch materials, identified by XRD, have been found in clay pots from Roman York, and are suggestive of primary production on a very small scale at some point in the late 2nd and early 3rd centuries A.D.\textsuperscript{300} Like the slags from Sagalassos, these are of quite atypical compositions that do not closely match glass samples from the surrounding region; high iron and aluminum levels suggest a poor quality sand, and high potassium suggests contamination with fuel ash. From Roman Italy, we have nothing at all, despite what the testimony of Pliny the Elder (see section 3) might lead us to expect. The character of the archaeological evidence thus leaves significant gaps in both space and time. Inferences based on chemical evidence can help to fill these gaps.

Of foundational importance to archaeological glass analysis, despite its brevity, is a landmark 1961 article by Edward Sayre and Ray Smith, which sets out five broad compositional categories of European, North African, and Near Eastern glasses, spanning the entire period from the 15th century B.C. to the 12th century A.D. Sayre and Smith used early forms of atomic emission spectroscopy to characterize two hundred samples of ancient glasses from several different museums, universities,

\textsuperscript{298} Rebourg 1989. To my knowledge, the glass adhering to the floors of these tanks has not been chemically characterized.
\textsuperscript{299} Henderson 2013, p. 231; Foy et al. 2000, p. 51.
\textsuperscript{300} Jackson et al. 1998; Jackson et al. 2003.
excavations, and private collections.\textsuperscript{301} Most samples came from known find spots, or if not, demonstrated significant stylistic affinities to other samples with known find spots. Colored and novelty glasses were deliberately excluded, in order to avoid their more complex chemistry. “Roman” glass is the third of Sayre and Smith’s five groups, and includes the vast majority of their samples from west of the Euphrates between the 4\textsuperscript{th} century B.C. and 9\textsuperscript{th} century A.D. It bears closest resemblance to their second group, which they call antimony-rich glass, the glass that dominated the Mediterranean region prior to the 4\textsuperscript{th} century B.C. and remained common east of the Euphrates until late antiquity, speaking to the survival of natron glassmaking traditions distinct from the Hellenistic and Roman koine. The main difference between the two is the use of manganese as a decolorant in Hellenistic and Roman glass, in place of the antimony favored by the older group. These two groups of glasses are distinguished from the Bronze Age (primarily Egyptian) glasses which preceded them and the Islamic glasses of the early Mediaeval period (Sayre and Smith’s first and fourth groups) by their comparatively low magnesium and potassium levels. The fifth and final group is a rare and relatively late offshoot of the Islamic tradition characterised by its extremely high lead content (these glasses contain upwards of 30\% lead oxide).

Compositions consistent with Sayre and Smith’s Bronze Age, “Roman,” and Islamic groups had been reported in literature before this publication.\textsuperscript{302} It had also already been suggested that, as is now generally agreed, the distinctive high magnesium and potassium levels evident in Bronze Age or Islamic glasses (as well as, we now know, many Persian glasses of the first millennium A.D.) result from the use of plant ash as

\textsuperscript{301} Sayre and Smith 1961, p. 1824.

\textsuperscript{302} A representative selection of analyses can be found in Caley 1957.
a flux, in contrast to the use of natron in classical antiquity. However, Sayre and Smith’s work was among the first attempts to create a rigorous, broadly applicable classification scheme with potential archaeological value, based on the systematic analysis of a large set of samples. Already in this article we see efforts to link chemistry with both geography and cultural change, and the authors expressed a hope that more precise future analyses (they suggested neutron activation) would permit the identification of specific raw material sources.

Over the subsequent decades of analyses, Roman glass, particularly in the western half of the Roman Empire, developed a reputation for exceptional homogeneity in its chemical composition. This is illustrated neatly by a collection of analyses, mostly by ICP-AES and ICP-MS, compiled by Maurice Picon and Michèle Vichy.303 These draw heavily on their own earlier work with Danièle Foy and Marie-Dominique Nenna, and include several dozen samples of natron glass, mostly uncolored raw glass where possible, from all around the Roman world, and from contexts dated from the last few centuries B.C. through the first millennium A.D.304 Twelve compositional groups are identified, nine occurring during the Roman period, most of those exclusive to late antiquity. Group 3 utterly dominates the glass finds of western Europe, both during the Roman period and well into the early Middle Ages, accounting for 90% of the samples in Picon and Vichy’s aggregated study. The eastern Empire also favors this group over all others throughout most of the period of study, but exhibits greater variability, both in the number of other groups present and in the frequency of those groups within the data set. Furthermore, none of Picon and Vichy’s groups occur in the west and not the east. Both of these factors could be

303 Picon and Vichy 2003.
taken to suggest that the ability to produce raw glass on an industrial scale was exclusive to the eastern half of the Roman Empire.

The “standard” composition of Roman glass, represented by Foy’s group 3, is characterized by high silica (about 70%) and soda (about 17%) content, moderate lime (about 8%) content, and comparatively low levels of iron oxide (less than 1%) and certain trace elements such as chromium.\(^{305}\) These latter features suggest that it was made using a pure, high-quality sand. Most uncolored Roman glass (colorless or decolorized glass, obviously, has an altered composition) falls somewhere close to this baseline. The dominance of a single compositional group throughout the Empire is suggestive of an almost exclusive reliance on a surprisingly narrow range of resources. Similarly, the distribution of minority groups seems to imply that, for whatever reason, the ability to make raw glass independently of this centralized production was largely restricted to the eastern regions. Most of these are represented primarily by finds from Egypt, where the raw glass is presumed to have been made; glass from Roman Egypt is often radically different from the “standard” composition, particularly in regard to calcium levels.\(^{306}\) Nenna \textit{et al.} attribute this to the use of local sands; desert sand, of course, does not generally contain shell fragments, and is therefore much lower in calcium carbonate than beach sand.

In late antiquity, beginning probably at some point in the 4\(^{\text{th}}\) century A.D., the impression of uniformity began to break down somewhat. Concerning the late antique and early Mediaeval Near East, scholarship mainly accepts five important groups defined in the work of Ian Freestone on Byzantine and Islamic glass, each

\(^{305}\) Picon and Vichy 2003, pp. 18, 22.  
\(^{306}\) Nenna \textit{et al.} 2000, p. 105.
corresponding more or less to late groups from the work of Foy, Picon, and Vichy; these are Levantine I (the group that includes the glass of Jalame; possibly equivalent or related to Foy group 3; see below) and II (Foy group 7), Egypt I and II (Foy groups 8 and 9, respectively), and HIMT (Foy group 1; 2 is closely related).\textsuperscript{307} Egypt I and II belong to the Islamic period. Levantine II, first associated with an important Islamic period glassmaking site at Bet Eli’ezer, appears to represent production in the southern Levant, as distinct from the northern Levantine production attested in the literary sources. This group has not been recognized in the Roman period either, but Julian Henderson has suggested that some of its traits, particularly its high zirconium levels compared to Levantine I, are reminiscent of XRF and ICP-MS data on a few samples from Pompeii studied by a team from the University of Calabria.\textsuperscript{308} These might be the products of a primary glass center operating elsewhere in the southern Levant during the 1\textsuperscript{st} century A.D., which is not attested in the archaeology or literature.

The most important of the new groups introduced in late antiquity is that known as HIMT, or High-Iron, -Manganese and -Titanium, which is roughly two or three times richer in all three of these minor elements than typical Roman glass.\textsuperscript{309} Foy \textit{et al.} opine that, while the manganese is likely to have been a deliberate addition to control the color of the glass (an olive green that can be readily distinguished from the blue-green of Levantine I or earlier Roman uncolored glass), the iron and titanium are probably derived mainly from impurities in the sand.\textsuperscript{310} HIMT was first explicitly

\begin{thebibliography}{99}
\bibitem{307} e.g. Freestone 2006, p. 208.
\bibitem{308} Henderson 2013, p. 241; de Francesco \textit{et al.} 2010.
\bibitem{309} Freestone 1994.
\bibitem{310} Foy \textit{et al.} 2000, p. 54. On the color chemistry of HIMT, see also Freestone \textit{et al.} 2005, p. 156.
\end{thebibliography}
defined by Freestone in an SEM-EDX analysis of three samples of cullet taken from
the late 1970s British Academy excavations at Roman Carthage. Since then, it has
been identified at sites around the Roman world, beginning in the late 4th century
A.D. and continuing well into the Mediaeval period. It is generally thought quite
likely that HIMT was made somewhere in Egypt using local sand and natron, based
on similarities to the compositions of other Egyptian groups, but few scholars would
be willing to treat this matter as conclusively settled.311 It may even have been made
from a mixture of two sand sources or two raw glasses.312 HIMT glass is not as
universal as the earlier Roman type; it dominates some sites while being unknown at
others nearby. Some studies of the use of different compositions at individual sites
have suggested that differential access to glass types may be a matter of a site’s
prominence or status; in many cases, it seems probable that raw HIMT is a relatively
expensive import, while compositions more in line with the older “standard” in
isolated locations may be the product of recycling.313

The late antique Levantine I group, of which the late 4th century A.D. glasses
analyzed by Brill at Jalame are among the earliest examples, is sometimes seen as a
continuation of Foy’s group 3, the typical “Roman” glass, which is the only one of the
twelve groups enumerated by Picon and Vichy that provides a close match for it.314
Picon and Vichy themselves believe that the groups are derived from the same source
of sand, and furthermore, based on Brill’s work (see section 3), that this source is
likely to be the River Belus. However, the match is not exact, as earlier Roman glass

311 Freestone et al. 2005.
312 Freestone et al. 2005, p. 155; Degryse et al. 2006, p. 496.
313 e.g. Arletti et al 2008, p. 619; Schibile and Degryse 2013, p. 168; Cholokova
2014, p. 102.
314 Picon and Vichy 2003, p. 23.
is generally somewhat lower in aluminum (it is important here that Freestone’s groups are defined by the ratio of lime to alumina in samples, on the grounds that both components are derived almost entirely from sand, and the ratio present in the original sand should therefore be preserved). Freestone himself has suggested that the difference might relate to subtle variations in the sedimentary output of the Nile (the ultimate source of most Levantine beach sand) over the centuries, but also makes cautious note of Pliny’s account of primary glassmaking in western Europe, where Foy’s group 3 is most prevalent.\(^{315}\) As Freestone’s work centers on the Byzantine and Islamic Near East, while Foy’s, though including samples from diverse regions and periods, has focused primarily on the western Mediterranean (and particularly on shipwrecks) during the High Imperial period, bridging the gaps between them is not a trivial matter. For the moment, then, it is difficult to be certain that the northern Levant was the ultimate source of most Roman glass before the 4\(^{th}\) century A.D., although based on this evidence it does seem likely.

Given Egypt’s apparent importance to the supply of natron in the ancient Mediterranean, it seems possible that any limitations on primary production of glass in the western Empire might be due to difficulty in obtaining this substance outside of the core glassmaking regions. The fact that Wadi Natrun itself apparently produced glass of a quite idiosyncratic composition further recommends the hypothesis; it can be conjectured that glassmakers there, but not elsewhere, were able to produce glass using their own local sands because they were able to access large quantities of natron with relative ease.\(^{316}\) Although it is plain from Pliny’s story about the invention of glass that transporting natron by sea was not considered unusual, the readiness with

\(^{315}\) Freestone 2006, p. 211.
which it dissolves in water may have made long-distance shipping of large quantities a difficult prospect.\textsuperscript{317} Moreover, there are few alternative sources of natron in the Roman world. Lake Van, in ancient Armenia (now within the borders of Turkey), is mentioned by Strabo (\textit{Geog.} 11.14.8), and Lake Pikrolimni, in ancient Macedonia, by Pliny (\textit{HN} 31.46). In both cases, chemical analyses of the modern lake water confirm that sodium carbonate could have been gathered at these sites.\textsuperscript{318} No other sources are known to have been exploited in the Roman period; furthermore, Andrew Shortland \textit{et al.} believe that the small size of Lake Pikrolimni and the remoteness of Lake Van would have made it difficult for either to produce natron in the kind of quantities required by the Roman glass industry.\textsuperscript{319} They further note that the timing of the switch from natron glass to plant ash glass during the Islamic period, which coincides with serious political disturbances in Egypt, is suggestive of Egypt being the only major source.

Recent promising research by Veerle Devulder \textit{et al.} has attempted to use boron isotope ratios to support the notion of exclusive reliance on Egypt for mineral flux.\textsuperscript{320} The Egyptian natron sources at Wadi Natrun and al-Barnuj have unusually high levels of $^{11}$B, which are closely matched by Roman natron glass samples from several regions. Pikrolimni natron, by contrast, is much closer to an average isotopic composition (samples from Lake Van, unfortunately, were not analyzed). These isotope ratios appear to support the model of an industry using only Egyptian natron,

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\item \textsuperscript{317} Kahn 2014, p. 132. For the same reason, there is no realistic possibility of finding a preserved cargo of natron in a shipwreck.
\item \textsuperscript{318} Shortland \textit{et al.} 2006, p. 524.
\item \textsuperscript{319} Shortland \textit{et al.} 2006, p. 524
\item \textsuperscript{320} Devulder \textit{et al.} 2014.
\end{itemize}
\end{footnotesize}
though the results are in some respects problematic and invite further investigation.\textsuperscript{321} Western primary glass production, then, would rely on either plant ash (which we know to be rare during the Roman period, though there are a few examples) or natron imported from Egypt as a flux. Importing natron does not seem out of the question. Romans of the Imperial period do not seem to have regarded it as being extremely difficult to obtain; it is readily prescribed for a number of ailments in Latin medical texts alongside perfectly mundane substances like olive oil, salt and honey (\textit{e.g.} Celsus, \textit{Med.} 3.21.11.4; Scribonius Largus, \textit{Compositiones} 8.1). However, these applications call only for very small amounts of natron; primary glass production on the model of the operation at Beirut would have required tons of the substance, and these quantities may have been more difficult to obtain in the west. In that case, we should expect primary production of glass to have been most economical in or near Egypt.

So far, we have seen evidence that suggests primary glass production on a large scale is likely to have been restricted to the Levant and Egypt during the Roman period. The case for the opposite view begins, naturally, with Pliny the Elder. Pliny testifies (see section 3) that, in his time, raw glass was made in Italy, Gaul and Spain, something he presents as a relatively recent development. It bears repeating here that archaeological evidence for primary glass production in the western half of the Roman Empire is thin on the ground, and much less clear-cut than the evidence from Beirut or Wadi Natrun; in Italy, despite Pliny’s assertions, there is none at all. However, it is worth bearing in mind that such sites are rare during the Roman period.

\textsuperscript{321} See Devulder \textit{et al.} 2014, pp. 111-112 for difficulties in interpreting their data conclusively.
even in the Levant and Egypt, where the majority of primary production is thought to have occurred. Moreover, it is difficult to explain why there should be little or no primary production in the west. Secondary production of glass vessels and windowpanes certainly seems to have been an active industry throughout the Empire from the first century A.D. onward.\textsuperscript{322} It also seems clear that, by the High Mediaeval period, much of the glass used in western Europe was the result of European primary production, using whatever resources were available in a given region.\textsuperscript{323} This glass is, by and large, of inferior quality to Roman natron glass, but its existence proves that there was no \textit{practical} barrier to widespread small- to medium-scale primary glass production in pre-modern Europe.

It seems possible that some of the numerous secondary production facilities for which we have evidence were also engaged in small-scale primary production, and that the vagaries of archaeological preservation have in most cases denied us the very specific types of evidence that would prove it (that is, partially melted batch materials). However, this is an unsatisfying and speculative argument. In a similarly unsatisfying and speculative vein, it is difficult to prove archaeologically that raw glass was traded outside of the Mediterranean basin during the Roman period. Most of our evidence for the shipping of raw chunk glass in the Imperial period is from shipwrecks; many cargoes contain both raw glass and finished vessels, though the lion’s share comes from just one, that at Embiez Ouest in southern France, which carried almost nothing else.\textsuperscript{324} Secondary production facilities in the Roman territories of northwest and central Europe appear to have produced glass vessels primarily from cullet (scrap

\textsuperscript{322} e.g. Arveiller-Dulong \textit{et al}. 2003 for glassworking in northern Gaul.
\textsuperscript{323} Picon and Vichy 2003, p. 27; Shortland \textit{et al}. 2006, p. 523; Fenzi \textit{et al}. 2013.
\textsuperscript{324} Fontaine and Foy 2007; Foy \textit{et al}. 2000.
glass destined for remelting), not large chunks of the kind we see in shipwrecks.\textsuperscript{325} It is difficult to imagine an entire industry sustained exclusively by recycled glass, however, particularly not one as vigorous as the glass industry in Roman Gaul and Britain. In short, it is hard not to feel that we are missing important evidence.

The work of Silvestri \textit{et al.} on the sand of the river Volturno in Campania (see section 3) has demonstrated that the composition of Roman glass can, in fact, be matched using imported natron and western Mediterranean sand, despite the earlier belief that these sands are too impure. In a similar vein, Dieter Brems and Patrick Degryse, although they did not make any experimental samples, calculated that the range of viable sand sources in Spain, France, and Italy increases greatly if we allow the option of adding extra calcium, in the form of crushed shell or limestone.\textsuperscript{326} The composition of the Volturno experimental glass was fairly consistent with Picon and Vichy’s group 3 with respect to its major and minor oxides (those of silicon, sodium, calcium, iron, aluminum, magnesium, and titanium), though it does diverge significantly with respect to some trace elements such as chromium.\textsuperscript{327} It performed similarly in comparison to the authors’ hypothetical “reference glass,” the averaged composition of eight samples from Pompeii. The deviations we see here are much smaller than those observed, for instance, in Egypt, where we know from archaeological finds that primary production occurred independently of the Levantine centers. The chemical signatures of separate primary production centers may therefore be more subtly differentiated than is at first apparent. It should be pointed out here that the most striking feature of “standard” Roman glass is its relative purity.

\textsuperscript{325} Baxter \textit{et al.} 2005, p. 48.
\textsuperscript{326} Brems and Degryse 2014, p. 122.
that is, Roman glass is high in silica, and low in most of the typical contaminants found in sand, like iron oxide and alumina (contrast HIMT). Although Belus sand is a good match in its natural state, it should not be surprising that deliberate action to purify sand from other locations might produce something similar.

An entirely different kind of challenge to the usual interpretation of homogeneity in Roman glass is Thilo Rehren’s suggestion that this is actually an artifact of a primary production process that involved the incomplete melting of ingredients.  As we have seen (section 2), silica glass could not practically have been made in the ancient world without the use of an alkali flux (whether this is natron or plant ash), whose function is to lower the melting point of the silica in sand. Different proportions of the major components in any mixture yield different melting points; the minimum possible melting point for a system is known as the “eutectic” point. In a system with three or more components, such as glass, there will be a range of related eutectic compositions, not just one. However, the basic theoretical principle, that there will be a narrow range of compositions with an “optimal” melting point, should still hold true. If the glass batch is melted completely and evenly, the glass will obviously include all of the batch material, and should therefore closely reflect the batch composition. If the batch is melted incompletely on the other hand, with significant amounts of the unmelted or partially reacted batch material lingering at the bottom of the furnace, the composition of the melt will instead tend towards the eutectic, provided there is no major deficiency in the quantity of any of the major components. A relatively wide range of possible batch compositions can thus converge to a much

328 Rehren 2000.
narrower range of final glass compositions, with variation largely a result of the maximum temperature reached during the melting process.

The “typical” composition of a Roman glass, outlined above, is very similar to the eutectic composition that we should expect from a method involving partial melting in a soda-lime-silica system. The picture of homogeneity that we derive by focusing on the major oxides present in Roman glass may thus be more reflective of technology than of the geological sources of raw materials. This is not a conclusion to accept lightly. It would require us to assign to sheer coincidence successful attempts to derive recipes for Roman glass based on the assumption of complete melting, like Brill’s calculations using Belus sand and Egyptian natron, or Silvestri et al.’s experiments with Volturno sand. This seems an unsatisfying result. Furthermore, it is unclear how the minor components like iron oxide and alumina (which in Rehren’s article are dealt with by assimilating them to whichever of the major oxides is most chemically similar, e.g. counting MgO with CaO) would affect the system. It is also unclear what archaeological evidence we might expect as confirmation of Rehren’s hypothesis; by ethnographic analogy with glassmakers still using traditional methods today, we should probably expect any remnants of the initial batch or partially fused material simply to be recycled into the next batch.

329 Rehren 2000, pp. 1229-1231. By contrast, glasses from Iron Age Europe, or from Egypt prior to the reign of Amenhotep II, exhibit significantly greater heterogeneity in their major element composition and do not approach a eutectic composition so closely. Rehren believes that this is evidence for complete melting, probably at higher temperatures (and therefore greater fuel costs) than were necessary for Roman or later Egyptian glassmaking.

330 Jackson et al. 2003, p. 34.

These reservations aside, it is worth considering the implications of the hypothesis. If correct, Rehren’s model would suggest that compositional homogeneity is strictly a feature of Roman glassmaking technology; specifically, of a realization that incomplete batch melting would allow the production of glass with more consistent quality and working properties. Although the model allows the possibility of major primary production in the west, it does not make it probable, as that would imply the fairly rapid spread of a glassmaking technology based on partial melting from the Levant to all parts of the Empire except Egypt, where quite different glass compositions exist – a curious conclusion indeed. However, it would mean that close attention to variations in the major element composition of glass is largely wasted; these could be attributed primarily to fluctuations in furnace temperature or possibly to different mixing methods. For data that can be used to extrapolate the locations of manufacturing sites, we ought to be looking more closely, to trace element compositions and isotope ratios.

In this vein, neodymium isotope analysis has been employed productively in recent years to suggest a broader production base for Roman glass than the straightforward compositional data might suggest. As described above, the unusual isotopic composition of Nile sediment makes it possible to distinguish eastern Mediterranean beach sands from western Mediterranean ones (the same is not true of the Egyptian desert sand used at Wadi Natrun, which is much more similar to western Mediterranean sediment, but as we have seen this is distinguishable by its major element composition anyway). Samples of glass analyzed by Patrick Degryse and Jens Schneider reveal that, until at least the 3rd century A.D., “western” (or at least mixed, possibly due to recycling) neodymium signatures can be found in uncolored
glass samples from sites in Belgium, the Netherlands, Slovenia, and Turkey. These are dominant at the European sites, while the Turkish samples (from Sagalassos) are closer to an even split between “western” and “Levantine” signatures. It would be nonsensical to imagine that sand was shipped from the western Mediterranean to major glass production centers in the Levant, when high-quality sand was available locally. The most natural explanation for the data appears to be that the raw glass used to make many of the objects sampled, regardless of how they ultimately reached their archaeological find spots, was originally created at unknown primary production sites not in the Belus region, but in Italy, Gaul, or Spain, from local sands. For once, the data seems mercifully clear-cut on this point; however, neodymium isotope analysis is still a new technique in glass studies, and has yet to see extensive use beyond the foundational work of a few geochemists.

It should be noted that the sample set examined by Degryse and Schneider is far from ideal. Of the five sites in the study, four are represented by six samples each or fewer (unsurprisingly, considering the destructive nature of current isotopic analysis methods), and they do not provide basic compositional data for their samples, though it seems natural to assume that they are all of typical Roman composition. They also do not give values for any archaeological glass found at sites in the Levant or Egypt, though they do analyze sand samples from the mouth of the Belus (originally collected by Brill during his work at Jalame, and still housed at the Corning Museum of Glass). Their previous work on Egyptian glass, which they cite, covers only samples of Byzantine and Islamic date. There is therefore no data for archaeological glass samples from the period of study that would be a priori expected to display

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“eastern” neodymium signatures, which is troubling from a methodological standpoint. Their justification, that the ratio of $^{143}$Nd to $^{144}$Nd would not be meaningfully altered by the physical processes involved in glassmaking, is not unreasonable, and for the purposes of their argument it is enough to show that some of their northern European samples have an isotope signature inconsistent with that of Levantine sand, which they do analyze. Moreover, this study is essentially a “proof of concept” for neodymium isotope analysis, meant more to recommend the technique for further use than to conclude any debates; finding any samples at all with an isotope composition that cannot be Levantine is a positive result. Nonetheless, a better “control group,” in the form of samples from Levantine sites, would have made the study more persuasive, and more information about the samples that were examined would have made its implications clearer.

Isotopic analyses have also been used to push a much more surprising claim – that raw glass was being made at Roman sites in the Eifel region of western Germany during the 4th century A.D. Hans Wedepohl and Albrecht Baumann argued this in an important study in 2000, based on lead isotope composition and trace elements, and also used strontium isotopes to suggest the deliberate addition of crushed shell to glass as a calcium supplement. Though their ultimate conclusions about German primary glassmaking have not been widely accepted, the underlying logic of their use of lead and strontium isotope compositions has influenced a great deal of subsequent work on Byzantine and Islamic glass in the Near East, and their work is thus worth some attention. Six samples, including two from a secondary glass workshop, two from tombs at the same site, and two from tombs at another nearby site, were

333 Leslie et al. 2006; Freestone et al. 2003.
analyzed by MS to determine their Sr and Pb isotope composition; the same samples
(along with many others from the area) had previously been characterized by XRF.\textsuperscript{334}
One sample was cobalt blue, and contained large amounts (greater than 1000 ppm) of
lead associated with the cobalt ore, which would not have been available in the local
area, but most of the others had intermediate levels (50-150 ppm), which Wedepohl
and Baumann attribute to river sand from an area with exposed deposits of lead ore,
like those found in the Eifel. The $^{206}\text{Pb}:^{204}\text{Pb}$, $^{207}\text{Pb}:^{204}\text{Pb}$, and $^{208}\text{Pb}:^{204}\text{Pb}$ ratios of
these deposits are similar those observed in the glass samples. In addition, the
German glass samples exhibit high, but variable, levels of barium, which is consistent
with the use of sands containing barite ($\text{BaSO}_4$), again like sands from the Eifel. It
should be noted here, however, that these points only make their analyzed
compositions consistent with a primary origin in the Eifel; Wedepohl and Baumann
do not make any clear efforts in this article to rule out any other possible regions with
similar geological characteristics.

The strontium isotope signatures of Wedepohl and Baumann’s samples are also
interesting; they appear to be much too low in $^{87}\text{Sr}$, relative to $^{86}\text{Sr}$, to have been made
using limestone as their calcium source. They therefore argued for the incorporation
of calcium into glass in the form of crushed shell, added separately from sand, both in
these six samples, and in others from Britain and central Europe analyzed in earlier
studies.\textsuperscript{335} Freestone, on the other hand, favors interpreting their data as representing
sand that contained large quantities of crushed shell, with no separate calcium-bearing
ingredient at all, exactly as we should expect of beach sand (and, indeed, exactly as

\textsuperscript{334} Wedepohl and Baumann 2000, pp. 129-130.
\textsuperscript{335} Wedepohl and Baumann 2000, p. 130.
we see in late antique Levantine glass).\textsuperscript{336} Wedepohl and Baumann do not appear to consider this possibility, presumably because the river sands of the Eifel region contain calcium carbonate only in the form of limestone, not shell. Pliny does mention the use of shell (\textit{conchae}) as a separate ingredient in glass; it is among those that he appears to consider non-essential (\textit{HN} 36.66). Wedepohl and Baumann take the much stronger line that “the Roman glass factories of the Imperial period were strictly advised to use the brittle marine molluskan shells in addition to soda… and quartz sand for their glass,” though they do not make clear by whom this advice might have been strictly given.\textsuperscript{337} The data available at present does not require the addition of shell, though it is difficult to eliminate the possibility, especially if we accept the authors’ other arguments for locating the sand source in inland Germany.

Freestone has pointed out that the lead isotope composition of these glasses is in line with that of HIMT glass; Wedepohl and Baumann’s descriptions of their uncolored samples as “green” and “olive green” are also consistent with this, and they mention iron oxide levels in excess of 2\% for other samples from the region.\textsuperscript{338} It is perhaps worth considering that technological factors, whether related to partial melting or modification of sand, might have allowed Roman glassmakers in diverse regions to mimic the HIMT composition, in the same way as they are argued to have mimicked the “standard” Levantine composition. Methods such as these should not have altered the lead isotope composition, but, as mentioned above, Wedepohl and Baumann believe their samples’ lead composition is consistent with that of local lead ores anyway. If we accept the existence of primary glassmaking in Italy during the 1st

\textsuperscript{336} Freestone \textit{et al.} 2003, p. 29.
\textsuperscript{337} Wedepohl and Baumann 2000, p. 130.
\textsuperscript{338} Freestone 2006, p. 207; Wedepohl and Baumann 2000, p. 130.
century A.D., it would hardly seem surprising to find evidence for the spread of the Technology to northern Europe by late antiquity, but at this point it is difficult to be confident.

Conclusion

While it is somewhat unsatisfying to resort to the archaeometrist’s never-ending cry of “more data!”, there are certainly gaps to fill in our knowledge of Roman glass compositions. The western Mediterranean in the first three centuries A.D. is well covered by Foy and her colleagues; late antiquity in the east is ably championed by Freestone, but slight discrepancies in their results and interpretations make it difficult to be certain of the “big picture.” The Hellenistic glass industry, from which the Roman industry presumably developed, is also tremendously understudied, and it is unclear how the existing primary glass industry of the Levant was affected by the establishment of Roman rule in the area during the 1st century B.C. (if at all). As a result, we may be missing key context for the origins of compositional homogeneity in the glasswares of classical antiquity. Henderson has expressed high hopes for the future use of Nd and Sr isotope ratios, as seen in Roman glass studies, in characterizing well-dated Hellenistic vessel glass from the Levant.\textsuperscript{339} In addition, as Picon and Vichy note, we are worryingly short of geological samples of Levantine sand.\textsuperscript{340} Western Mediterranean sands have recently been characterized in some detail by Dieter Brems et al., mainly with the aim of creating a reference database for Nd isotope analysis, but for Levantine sands, studies today still quote the AAS

\textsuperscript{339} Henderson 2013, p. 247.
\textsuperscript{340} Picon and Vichy 2003, p. 22.
characterizations of Belus sand published by Brill with the Jalame material.\footnote{Brems \textit{et al.} 2013a and b; Brill 1988, pp. 270-271.} It is, granted, more difficult to identify one-to-one correspondences between glass compositions and raw material sources than it is for pottery, but more reference data for the eastern Mediterranean would still be helpful.

We must not only acquire more data, however; we must do so with a clear awareness of how those data will fit into our understanding of glass production in the Roman world. In order for this to happen, archaeologists must take an active role in designing analytical strategies, selecting samples, and interpreting results. The role of archaeologists, and the interpretation of archaeometric data in its wider context, will be the focus of the next chapter of this review.
Section 5: The Historical Importance of Glass Analyses

The primary task of this section is to situate the existing work on chemical analysis of ancient glass (described in section 4) within the broader context of the “big questions” of Roman archaeology, and suggest ways for further work to make contributions. This kind of integration is perhaps the most difficult aspect of working with “hard” scientific data in an archaeological setting, and accordingly it is where much work falls short of its potential. Problems in the area of glass studies mirror persistent difficulties in the wider field of archaeometric research. Sustained consideration of analytical work from this perspective should greatly clarify the necessary and appropriate direction of future studies.

Archaeometry and Archaeology

It has been recognized for decades that archaeometric investigations regularly suffer major shortcomings in their integration into archaeological theory and problems. Individual perspectives on the state of the field can vary wildly.\textsuperscript{342} In general, though, progress towards solutions has been slow, and complaints made in the last decades of the 20\textsuperscript{th} century often remain relevant today. This is particularly true in classical archaeology, a field that tends to be a follower rather than a leader within the discipline of archaeology. Moreover, archaeology itself tends to lag a decade or two behind methodological breakthroughs in anthropology.\textsuperscript{343} The difficulties may also be due in part to the fact that progress demands changes not only in our ways of

\textsuperscript{342} e.g. Jones 2004, and the collected responses of Boivin \textit{et al.} 2005, especially the rather acerbic section by David Killick.

\textsuperscript{343} Boivin \textit{et al.} 2005, p. 183.
thinking but in the very culture of academia – a stubborn beast at the best of times. Emphasis on individual achievement, and the privileging of first or sole authorship when a scholar’s work is reviewed during tenure decisions, discourages specialists from devoting significant personal resources to their interdisciplinary projects.\footnote{De Atley and Bishop 1991, p. 379.} This is perhaps particularly true from the perspective of the humanities, where single-author papers are the norm. Furthermore, rivalry over theoretical paradigms, acrimonious enough within disciplines, can be even worse between them, further generating reluctance to work across disciplinary boundaries.\footnote{Rice 1996, p. 188.} One common complaint is that work trying to be “interdisciplinary” instead succeeds only in being “multidisciplinary” – for instance, haphazardly tacking specialist studies onto the end of site reports as appendices, with little reference to the overall interpretation of the site.\footnote{De Atley and Bishop 1991, p. 360.} Chemical analysis of pottery, in particular, has a reputation (perhaps more so than it deserves today) for being used as a flashy novelty, with its most significant contribution to archaeological site reports being an obligatory veneer of scientific objectivity.\footnote{Rice 1996, p. 168.}

The fact of a study’s creativity or methodological soundness from a physical science perspective is generally not the issue. Much of the recent work on identifying the raw material sources of Roman glass, for example, has made extensive, innovative use of variables that were not measured in archaeological glass at all until quite recently, such as neodymium and strontium isotope ratios.\footnote{e.g. Brems et al. 2013a and b.} This is the key skill that characterizes archaeometry (and, in a way, archaeology as a whole): the ability to
identify measurable physical and chemical parameters of artifacts, which can, by some logical inference, serve as proxies for social and cultural factors.\textsuperscript{349} In the studies we have seen, and in the earlier work on pottery that inspired them, aspects of composition are linked to geographical origin; we can thus make inferences about the movement of either raw materials or of the object itself during its use-life. Any well-written archaeometric article will explain this level of interpretation.

What is often missing here, even from relatively good work, is the next step: explication of the historical relevance of these inferences, either as a general principle or in the specific case of the artifacts in the sample set. By their nature, “scientific” studies of artifacts produce mainly information about manufacturing processes and raw materials. It could be argued that there is inherent value to this kind of information; studying how artifacts were made can undeniably be interesting in itself, and the “cutting-edge” flair of it all can, if nothing else, be conducive to public engagement. However, archaeological inquiry at the academic level today primarily concerns itself with attempting to look past the artifacts, into the lives, decisions, and “identities,” to use the favored buzzword, of the people who made them. In studies that source raw materials, it is easy to become complacent in this respect, since their general principle, that long-distance exchange can be reconstructed from compositional data, is so well-established by decades of work on pottery. As such, the value of these reconstructions is almost taken as read. There is a world of difference, however, between agreeing that a method has broadly applicable merit, and demonstrating the specific contribution of a single study to ongoing debate. It should be possible to appreciate, from reading an article in isolation, not only that a

\textsuperscript{349} De Atley and Bishop 1991, p. 370.
given site used a given proportion of imported wares at a given time, but also why that is significant in the context of the site’s history.

The extra step is a difficult one, and it is hard to blame the archaeometrists, for whom archaeological theory may be unfamiliar, and tangential to their main research interests. Moreover, the modern scientific tradition can be uneasy with the sort of inductive leaps that are often necessary to produce meaningful conclusions in the humanities.\textsuperscript{350} Unfortunately, when that step is not taken, archaeologists may be left wondering what the point is supposed to have been, and archaeometry’s reputation for irrelevance worsens.\textsuperscript{351} In part, this shortcoming may be a reflection of the sharp distinction in scientific literature between primary studies, which produce data and interpret its “literal” meaning (translating, for instance, a series of X-ray pulses into a statement about the calcium content of a sample), and secondary studies, which draw upon many primary studies to produce broadly applicable statements. There certainly are, in the humanities, publications that exist mainly to present new evidence, but the distinction is not as sharp, and often not as explicit. The job of the archaeometric team, from a scientist’s perspective, is to craft the experimental method, gather the data, and select an appropriate statistical treatment that will refine it into a coherent and reliable statement about the \textit{material} properties of the artifacts under study. This, in the physical sciences, would be a perfectly satisfactory result in itself, and indeed it could be argued that adding more would bloat and muddle a perfectly good self-contained chemical analysis.

\textsuperscript{351} Killick and Young 1997, p. 518.
The task of integrating the “hard data” into existing debates about the societies of the ancient world, then, is left to the archaeologists. They, however, often shy away from reliance on analytical techniques they feel they do not fully understand, and regard them as the province of a few dedicated specialists.\(^\text{352}\) It is, again, hard to blame them, as many have never been trained in the use of chemical data.\(^\text{353}\) In the words of Chris Gosden, “Science is Hard,” both in the sense that it is difficult, and in the sense that, just as scientists are uncomfortable with major leaps of inference, we are uncomfortable with anything that makes a claim to objective fact.\(^\text{354}\) Nonetheless, it is not necessary that all archaeologists be able to plan and lead archaeometric studies. Simply acquiring the basic scientific literacy necessary to follow their logic, apply their conclusions judiciously, and perhaps make suggestions for future applications of successful techniques, is perfectly achievable.

In this vein, it is worth noting that handbooks and guides on archaeometry, in the same way as individual studies, regularly spend the most time on scientific and technical aspects of the techniques. Good ones also discuss statistical treatment of data, an area in which many archaeologists struggle. Exposure to these ideas is crucial for archaeologists wishing to employ archaeometry in an informed manner, whether in projects of their own or in broad synthetic works. However, even the best of such publications are typically light on interpretation and archaeological theory,

\(^{352}\) Boivin et al. 2005, p. 183

\(^{353}\) Killick and Young 1997. The somewhat dire situation they describe in 1997, with only a dozen US archaeology departments even offering graduate survey courses in archaeometry, and only two or three requiring that students take one, is much improved today. However, it is still far from satisfactory, particularly in the archaeology of the classical Mediterranean.

and do not equip readers to “bridge the gap,” as it were.355 They describe the properties of archaeological materials, and how we may quantify those properties, but they do little to explain why quantifying them should be desirable in the first place. Here, more extensive use of case studies or “success stories” would be welcome additions. In introducing the concept of sourcing the raw materials of pottery by examining their chemical composition, for instance, one might cite the work of the University of Leuven team at Sagalassos (techniques included AES, AAS, NAA and XRF) in identifying the different clay sources used by the potters of the ancient city.356 These results were ultimately used to argue that the potters were willing to travel further afield to collect higher quality clays for the city’s export-quality fine wares, while using clay from within the potter’s quarter itself for more utilitarian applications.

Archaeometry is an expensive, time-consuming aspect of an expensive, time-consuming business, and requires access to specialized skills that archaeologists do not normally possess. It must be able to pull its weight from an interpretative standpoint, if its use is to be justified, and only willingness on the part of archaeologists to engage with scientific data on its own terms will make this happen. The remainder of this chapter will attempt to show how we can progress in this direction, in the case of Roman glass chemistry.

355 See e.g. Goffer 2007.
Archaeometry and Glass Studies

Ancient glass studies in general, curiously, tend to suffer from a similar malady to archaeometric work in general: poor integration, often due to a lack of expertise. No sensibly run Mediterranean excavation would lack specialists in pottery, and few today would neglect to bring an osteologist, but most sites can get away with having no dedicated glass specialist. As a result, full publication of glass often occurs separately from the main publication of the site.\textsuperscript{357} When there is a catalogue written by a glass specialist in the main publication, this person may not actually have been involved with the excavation.\textsuperscript{358} Furthermore, it is relatively unusual for archaeological glass specialists to have practical experience in working with glass, except in the unusual case of glassblowers that later become archaeologists (notably Marianne Stern and Alysia Fischer).\textsuperscript{359} Attempting to resolve these factors is rather beyond the scope of this thesis; however, it is important to be aware from the outset that we are dealing not only with a sometimes controversial branch of archaeology, but also with an artifact type that many archaeologists are likely to regard as comparatively esoteric.

\textsuperscript{357} For example, most of the finds and architecture from Frank Brown’s excavations at Cosa were published in the \textit{Memoirs of the American Academy in Rome} (lamps and coins occupied a whole volume each; pottery received two), while David Grose’s work on the tens of thousands of pieces of glass from the site appeared only in publications of the Association Internationale pour l'Histoire du Verre (Grose 1974).
\textsuperscript{358} Fischer 2008, p. 5.
\textsuperscript{359} Fischer 2008, pp. 6-7. Contrast the academic culture of, in particular, lithic specialists, in which practical experience making stone tools is almost a rite of passage; pottery experts too can commonly boast of at least rudimentary practical skill with their material. Most glassworking disciplines are less accessible than these, as well as being a potentially dangerous pursuit for the unskilled.
As we have seen (see section 4), most archaeometric analyses of ancient glass today are compositional or isotopic studies aimed primarily at tracing the geological sources of raw materials. From an archaeological or historical perspective, a number of shortcomings appear to be endemic to this kind of work. Sample selection is sometimes not discussed at all, leaving the reader to assume that the analysts simply took whatever excavators or curators were willing to give them.\textsuperscript{360} This seems particularly likely in the case of techniques that require powdered samples, notably isotopic studies; excavators, understandably, are often reluctant to relinquish their finds for such purposes. The archaeological context of samples, similarly, is generally not of great concern, and is often not described at all beyond offering a date range. Many archaeometric studies also do not include any description or discussion of their samples’ stylistic traits. Those that do explicitly concern themselves with such features, such as the work of Mike Baxter, Hilary Cool, and Caroline Jackson on the Roman glass of Colchester, are among the most thought-provoking examples of their kind, as they are able to pose much more specific questions about the manufacture of particular artifact types.\textsuperscript{361} Citations of Pliny the Elder’s \textit{Natural History} are common, almost obligatory, as it is on his word that we first hypothesized the existence of primary glassworking industries in the Roman west. Detailed discussion of the text (including, for example, why we might or might not consider Pliny worth believing, or whether his description implies any differences between the western and eastern industries) is not.

\textsuperscript{360} \textit{e.g.} Aerts \textit{et al.} 2003.
\textsuperscript{361} Baxter \textit{et al.} 2005.
Patrick Degryse and Jens Schneider’s work on neodymium isotope ratios in Roman glass provides an illustrative example.\(^{362}\) As we saw in the previous section, their ideas are extremely important methodologically, as the data produced by their technique is among the most convincing threads of evidence in favor of the existence (making no attempt for the moment to speak for the extent) of primary glass production in the Roman west. From a geological perspective, this conclusion is difficult to dispute. However, they describe their samples in only the barest of detail, and do not even include conventional compositional data for them (one assumes that such data does exist, as they confidently describe their samples as “natron glass,” but it is not made clear whether or where this has been published). This makes it difficult to evaluate their ideas with any specificity. One would like, for instance, to be able to look for any correspondences between “eastern,” “western,” or “mixed” neodymium signatures, and style, color, working technique, or trace element profile, none of which is mentioned. Nor is there any breakdown of the stratigraphic dates of their samples from Sagalassos, which span some two hundred years (although, with only six samples from the site, it is unlikely that any apparent trends would be truly meaningful).

Degryse and Schneider are not to be faulted for all of this; they are geochemists, here writing an article that serves primarily as proof-of-concept for a new chemical analysis technique, not archaeologists (notwithstanding their earlier work on pottery and glass for the KU Leuven excavation at Sagalassos). As geochemists they are providing exactly the kind of technical insights that almost no professional archaeologist ever could. However, the gaps in their article’s coverage provide a

\(^{362}\) Degryse and Schneider 2008.
useful demonstration of a principle that should perhaps be intuitively obvious: if archaeologists want archaeometric articles that are interesting and useful to them, their active participation (and willingness to give up samples) is necessary. One could make a similar assessment of Degryse’s involvement in an ambitious attempt, headed by Dieter Brems, to map the neodymium isotope composition of beach sand from all along the Mediterranean coasts of Spain, France, and Italy. No archaeological material was analyzed at all in this particular project; the sole aim was the establishment of a database that will provide a reference for future glass analyses. The methodological value of such a project certainly deserves to be stressed, but even so, the addition of even a single Roman archaeologist to the list of ten authors might have given some useful context. The relevant geological traits of each characterized region are discussed at length. However, not even the faintest allusion is made as to why an archaeologist or historian might care about the presence or absence of a glass factory in any of these places. Even the obligatory Pliny reference appears only in a companion article focusing on strontium isotopes. The study’s aim is explicitly archaeological, but the publication reads as though written strictly by and for geochemists. As a result, it does nothing to promote the usefulness of neodymium isotope analyses to the people on whose behalf they are ostensibly being done.

In comparison to geochemical sourcing studies of more straightforward materials, obsidian being a resounding success story, studies of man-made glass are complicated by the fact that this material represents a mixture of raw ingredients. At minimum, glass will consist of a silica source and a flux; potentially we must also deal with an added calcium source, and colorants or decolorants. These factors can be treated as

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363 Brems et al. 2013b.
364 Henderson 2013, p. 306.
analogous to the alteration of pottery compositions by the presence of temper, or the modification of clay by washing and levigation, both of which can make it difficult to find a one-to-one correspondence between a pottery sample and a geological clay source. These complications are generally seen as obstacles, since they make it more difficult to isolate diagnostic features of a particular clay (or, in our case, sand) source within the complex chemical “fingerprint.” As Prudence Rice notes, however, those same irritating complications also mean that “human behavior and cultural choices are encoded in pottery, along with geochemical information on its source or ‘identity’.”

The same is true of glass, whose composition is the result of a recipe using (in typical Roman glasses) a carefully-selected sand source, which could potentially have been altered by washing and grinding; a natron flux, which occurred naturally in only one place in the empire; and colorants, which might have been old favorites of Pharaonic Egyptian glassmakers, or the secret ingredients of a rare novelty glass. The importance of information about raw material sources (and, by extrapolation, manufacturing locations) should not be downplayed; nor, however, should we imagine that this is all we are seeing, or all that we can use.

We know that glass artifacts from across the Roman Empire were broadly homogeneous in their chemical composition for several centuries, in stark contrast to the regionalism that can easily be detected in pottery. As we have seen, the evidence on the reasons for this homogeneity is equivocal. The “common sense” explanation would be the use of a geographically restricted range of raw materials, though some other data suggests that this may be an illusion created by aspects of the production process. Some authors have suggested that rigorous, even “ritualistic,” adherence to

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an established recipe, perhaps including some form of pre-treatment for the sand, could be responsible.\textsuperscript{366} Chemical studies of the last decade usually comment on which of the two main hypotheses, or any variants, is supported by their present data, but serious discussion of what either conclusion would imply is generally thin on the ground. If we are seeking to confirm or disprove, archaeologically, Pliny’s oft-cited statement about primary glass production in western Europe, then why is Pliny’s account important in the first place? Both possibilities should be starting points, not the final goal of research.

Alexander Aerts \textit{et al.} 2003 state a common view of the perceived homogeneity of Roman glass: “the strong constancy for much of the glass analyzed found in the Middle East and Europe for such a long period indicates that the production of the raw glass occurred in a very stable economic and political structure.”\textsuperscript{367} This interpretation of the data, while attractive, and in good accord with how we might like to view the broad impact of the \textit{Pax Romana}, is worryingly simplistic (and, at the risk of laboring a point, was written by a geochemist, not a historian). Quite apart from the uncertain logic of the relationship between manufacturing technology and political stability, it does not take into account all the political changes of the long period in which “Roman” glass was dominant. Whatever our views on the centralization or dispersion of the Roman glass industry, it is undeniable that the Levant was its heartland, and the stability of the Levant is not something to be assumed at any point in recorded history.

\textsuperscript{366} Jackson \textit{et al.} 2003, p. 33.  
\textsuperscript{367} Aerts \textit{et al.} 2003, p. 666.
The existence of a single dominant compositional group in the ancient glass industry is not a new development of the Imperial period, but a continuation of the state of affairs prevailing in the Hellenistic glass industry – one that apparently survived the turmoil of the Roman assimilation of the Near East over the course of the 1st century B.C. The glassmakers’ industry was evidently not broken by the gradual implosion of the Levant’s erstwhile rulers, the Seleucid Empire, or by that empire’s often-tumultuous relationship with Ptolemaic Egypt; nor was their access to natron disrupted by the fall of the last Ptolemy, Cleopatra VII. Later, the glass industry emerged, apparently unscathed, from the Jewish revolts of the 1st and 2nd centuries A.D. This is a doubly curious fact, when one considers the important place often ascribed to Jewish craftsmen in the development of the glass industry. Either the Levant is not as critical to the ancient glass industry as we might believe, or this non-essential primary industry was simply much more resilient to political upheaval than it has been given credit for; it may not have been subject to control by political authorities in the way that more valuable materials often are.

If all (or substantially all) Imperial Roman glass products were made using raw glass from the Levant, then this implies that raw glass production in other regions was undesirable, impractical, or simply impossible. It seems unlikely that the technology itself was inaccessible. On the basis of the way ancient authors talk about glass, Marianne Stern has argued that, during the Classical period, the actual processes by which raw glass was made were not common knowledge on the Greek mainland. It is possible that Greek glassworkers may not have known what was involved in primary production, or what the raw materials were. It seems clear that by the Roman

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369 Stern 2007, p. 368.
Imperial period, however, this was no longer any excuse. Pliny’s description of glassmaking, though not by any means a detailed technical explanation, shows that an upper-class Roman, well-educated but certainly not an expert, could give an account of what glass was, and how it was made, that we recognize today as basically correct. More detailed information would surely have been available to anyone willing to look for it.

The remoteness of Egypt’s supplies of natron, an essential ingredient for typical Roman soda-lime glass, is the next obvious explanation for why the Roman west might have chosen not to produce its own raw glass. This certainly seems to fit with the evidence of major and minor element composition. Although the main compositional groups that dominate the Roman and early Byzantine glass tradition are normally attributed to the northern Levant, Egypt appears to be responsible for a disproportionate number of lesser groups, particularly in late antiquity, suggesting that easy access to natron does, in fact, make regional production based on local sands more viable. However, though it is overwhelmingly dominant in our period, soda-lime technology is not the only reasonable way of making glass in the ancient world.

The prolific “forest glass” tradition that eventually replaced soda-lime in northern Europe during the Mediaeval period makes it clear that integrated primary and secondary production, based on a combination of wood ash with northern European beach or river sand, is eminently feasible, as others have noted. In Persia, a plant ash tradition continued without interruption throughout antiquity, suggesting that knowledge of that technology would have been available. Perhaps more to the point,

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370 Picon and Vichy 2003, p. 18.
371 Picon and Vichy 2003, p. 27.
plant ash glass is not unknown in Roman Europe. It always merits comment when it is identified by chemical analysis, and is unusual enough that it seems much more likely to have been imported, perhaps from Persia, than a product of a Roman ash glass industry, but it does not appear to be wholly alien to the Roman west. In fact, Pliny seems to be well aware of the uses and chemical properties shared by plant ash and natron, actually describing a substance made from *quercus cremata* as a variety of *nitrum*, though he notes that it was never made on a large scale, and believes it is no longer produced at all in his time (*HN* 31.46).

A full account of the question, then, requires us to explain, or at least suggest, why the Romans never produced plant or wood ash glass. One strong possibility is that, due to the extreme purity of Egyptian natron, any economic benefits to using locally available materials would have been more than outweighed by reductions in quality or the consistency of the glass’s working properties. Plant ash, unsurprisingly, is far more variable in composition, and the number of minor elements present in appreciable quantities is greater. Parthian and Sassanian glassmakers managed to achieve an impressive degree of consistency in their ash glasses, but researchers today remain uncertain as to how. It seems likely that they were very selective about the plants they used, and some form of quality control may have been in place; or they may have simply dealt with such vast quantities that any compositional variation was averaged out. Simply recognizing the conceptual soundness of ash glass would have been only the first of many steps in establishing a viable industry.

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372 e.g. Henderson 1996, p. 190; Mirti et al. 1993, p. 231.
373 Freestone 2006, p. 205.
It is important here that not all plant ash is created equal. Mediaeval Venetian glassmakers were apparently so dissatisfied with the inferior quality of forest glass that they routinely imported bulk quantities of the ash of halophytic desert plants from the Levant for their famously brilliant glassware. Venice even went so far as to pass a law during the late 13th century A.D. that forbade the city’s glassmakers from using inferior European fern ash, in order to protect the integrity of, as it were, the Venetian brand. The fact that such a law was thought necessary implies that some glassmakers, and presumably their customers, were in fact satisfied with the quality of ash glass made using local ingredients. However, the point stands: top quality glass demands top quality ingredients, and freedom from dependence on natron specifically would not necessarily have meant freedom from the need to import raw materials. An appreciation for quality (which consumers of Roman glass clearly had), combined with an aversion to the inherent risk of exploiting an unfamiliar raw material, would have gone a long way to discourage the establishment of a European primary industry.

Another, potentially related, possibility is that raw glass was simply so readily available in the Imperial period that there was no significant economic benefit to producing it locally in the western Empire. There was a place for secondary workshops, because they could tailor their output to suit local tastes, but glass was glass, regardless of the location of the primary facilities. Any special properties that might be required (color, for instance) could be achieved by making additions to the melt at the level of secondary production, according to an established recipe. This would imply that transporting Levantine raw glass to the workshops of Italy, Spain,

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Gaul, and even Britain was cheap enough, and provided large enough quantities, that any cost reduction associated with producing glass locally would have been negligible in comparison to the drawbacks outlined above. For the glassblowers, the time and effort they must have devoted to mastering their demanding craft would have seemed a questionable investment, if supplies of their raw material had been difficult to ensure.

The cost of resources involved in primary glass production on the Roman model is likely to have been extremely high. It is estimated, with general agreement, that making a large batch of glass from raw ingredients in a tank furnace, like those for which we have evidence at Beirut and Bet She’arim, would demand temperatures of at least 1050 ºC, sustained continuously for over a week. The fuel consumption of these furnaces must have been nothing short of astonishing, and may have been the most expensive aspect of the entire process. It is hardly surprising that, in the Byzantine and Islamic periods, when evidence for primary production sites is more plentiful, these tend to be temporary installations, set up near areas that would have been heavily forested in antiquity, and possibly in use for only a single season. There is no immediately obvious reason for high fuel requirements to have favored the Levant over western Europe, but certainly the “startup costs” of such a venture would have been daunting in a region that did not already have a history of primary glassmaking.

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377 Kowatli et al. 2006, p. 118.  
Comparisons to the Mediaeval European glass industry are again illustrative. In the
Mediaeval period, when evidence for primary glassmaking is abundant in western and
northern Europe, it tends to be done on a much smaller scale, and without the
separation of primary and secondary production that is commonly believed to have
been the norm in classical antiquity; that is, Mediaeval glass workshops made their
own glass from scratch.\textsuperscript{379} The structure of the industry presumably reflects the very
different sets of socioeconomic pressures faced by glassworkers during the two
periods. The Hellenistic, Roman, and Byzantine model implies that primary
glassmakers, or their benefactors, were able to organize the provision of labor, raw
materials (which, even in the Levant, would have been imported, in the case of
natron), fuel, and transport on a much greater scale than individual Mediaeval
glassmakers would have known what to do with. In the Levant, this industry was
apparently established before the Romans even arrived, and would have been the
model for any imitation by would-be western glassmakers. There is, again, no
immediately obvious reason for this to have made western primary production
impossible, but it is easy to see how the prospect might have been daunting.

In contrast to all of this, we can examine the consequences of the dispersed
production model. If all (or substantially all) Imperial Roman glass products were
roughly homogeneous in major and minor element composition, \textit{despite} significant
decentralization in production and resource exploitation during the first two or three
centuries A.D., then this would imply a surprising degree of technological
standardization. This remains, at present, a minority opinion, but one for which there
is interesting chemical evidence that demands further investigation, discussed in

\textsuperscript{379} Rehren and Freestone 2015, p. 236.
section 4; it has been argued that major element composition in glass may be more a result of production technology than of raw material, and isotope studies have pointed to the use of western Mediterranean (or at least non-Levantine) sand in at least some samples of glass from European sites. It is also difficult to ignore Pliny’s testimony on the matter (see section 3). The homogeneity of Roman glass stands in stark contrast to the variability that can easily be observed in other traditions of glassmaking where primary production took place at multiple widely dispersed sites, such as the Islamic and Mediaeval European glass industries. As in the case of centralized production, we must ask why the Roman glass industry might have organized itself in this fashion, but here the further question of how they did it is also raised.

Alberta Silvestri’s team demonstrated that viable “Roman” glass can be made from Campanian beach sand, if it is ground with a wooden mortar and pestle before fusion, in order to remove its “soft” components. Their method allows us to regard as plausible Pliny’s description of glassmaking at the mouth of the Volturnus, and accords well with the statement *harena alba... pila molave teritur*. This raises the question of how a would-be Italian glassmaker might have discovered such a technique for refining sand, to which the most immediately obvious answer is that it was suggested by analogy with trituration in the manufacture of pottery. However, the more pressing issue is that grinding these large quantities of sand simply seems unrealistically labor-intensive.

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Before giving too much weight to the labor requirements of purifying sand, it is worth looking for context. Bronze Age and Islamic plant ash glasses were often made using crushed, ground quartz pebbles rather than sand, possibly because this purer material produced better quality glass than sand would have.\textsuperscript{381} Quartz is a significantly harder material than the carbonates and aluminates that Silvestri et al. were able to strip from their Volturno sand, and grinding quartz pebbles would have been, if anything, an even more laborious process. Grinding and washing the sand before melting it is therefore not an inherently unreasonable notion. Admittedly, though, glass made with ground quartz in other periods is not the most relevant point of comparison; the method needs to have been competitive with the contemporary use of sand from the mouth of the Belus, which is generally thought to have been used unmodified.

Brill’s work at Jalame, including the samples of Belus sand that he took while in the area, is regularly cited as evidence that this sand was suitable for glassmaking in its natural state. Brill himself, however, does note variation in the composition of Belus beach sand; the natural action of wind and water produces areas of lighter and darker sand on the beach, with different ratios of calcium, aluminum, and iron.\textsuperscript{382} In fact, he attributes the small discrepancies in calcium content between his glass and sand samples to the occasional inclusion, whether by accident or design, of a shovelful of sand from a different beach zone. We should bear in mind that, in tank furnaces like those of Beirut and Bet She’arim, each melt would have required at least six tons of sand, and perhaps question the level of discernment that would have been possible in

\footnotesize{\textsuperscript{381} Tite \textit{et al.} 2002, pp. 586-588; Freestone 2006, pp. 205-206. The use of pure quartz is only viable for plant ash glass, since the calcium necessary to make the glass chemically stable is provided by the flux (see section 2).}

\footnotesize{\textsuperscript{382} Brill 1988, pp. 267-268.}
gathering these bulk quantities. It does not seem out of the question that a similar kind of pre-treatment to that described by Pliny, and tested by Silvestri et al., might already have been in use for Levantine sands, in order to ensure their consistency and quality. This is admittedly pure speculation, though, and difficult to reconcile with Pliny’s explicit contrast of a Sidonian *antiqua ratio vitri* against the Volturian production of his own time; he clearly believes that there is something innovative about the Italian method.

We are also required to postulate a means of supplying hypothetical western glassmakers with bulk natron. Regardless of whether we favor the existence of European glassmaking centers, the substance must have been shipped in large quantities from Egypt to the Levant (and possibly to Rhodes during the Hellenistic period); at any rate, Pliny does not seem to have any difficulty with the basic idea of transporting blocks of natron by sea. The question, one to be answered by archaeologists or economic historians, is whether this could have been a viable strategy for a would-be Italian glassmaker, whose locally-manufactured raw glass would compete with ingots imported from the Levant.

The alternatives to Egyptian natron, at present, seem unlikely. Shortland et al. identify only two plausible sources of natron outside Egypt; one in Armenia, and one in Macedonia, and boron isotope studies have cast serious doubt on any claims that might be made by the latter (see section 4). However, the exploitation of sources currently unknown to us cannot be ruled out; it is extremely likely that Middle Byzantine glassmakers had access to an Anatolian source that has yet to be identified,

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so we should not imagine that our knowledge of the available resources is complete.\textsuperscript{385} It is here worth remembering that the aforementioned boron isotope studies of Devulder \textit{et al}. conspicuously failed to demonstrate conclusively that Wadi Natrun really was the source (though it is by far the best of the known possibilities). Alternatively, it does not seem outlandish to think that Roman technology might have permitted the synthesis of natron (or a functionally equivalent sodium salt) from ordinary sea salt and limestone. On the other hand, the idea that this might have happened on an industrial scale, without leaving any archaeological or textual evidence, strains credulity.

If western primary glass manufacturing centers existed, then, they would not have freed the glass industry from dependence on Mediterranean shipping. Moreover, their products apparently do not differ from those of their eastern counterparts in any way that would have had great practical significance for glassworkers. What are we to imagine was the point? Perhaps natron was more easily transported by sea than raw glass, but this is tenuous speculation. Natron, being readily soluble in water, has never been found in a shipwreck, and likely never will be, so the proposition cannot realistically be tested. Moreover, we have ample evidence that Roman ships often carried large cargos of raw glass; indeed, the late 2\textsuperscript{nd} or early 3\textsuperscript{rd} century A.D. Ouest-Embiez shipwreck carried almost nothing else.\textsuperscript{386} Perhaps profit margins were improved by “cutting out the middle-man,” as it were, though this seems to imply a more calculating attitude on the Romans’ part towards their production chains than many of us might be comfortable with. Without a convincing answer to the question, archaeologists outside of the rather narrow archaeometric community are likely to

\textsuperscript{385} Rehren \textit{et al}. 2015, pp. 276-277.
\textsuperscript{386} Fontaine and Foy 2007.
remain both skeptical of the idea, and uninvested in the debate, regardless of any chemical evidence that is brought to bear.

The typically “Roman” soda-lime glass composition remains dominant throughout the Mediterranean world until approximately the 9th century A.D. Its eventual disappearance has been linked with centuries of instability in Egypt, the main source of essential natron, beginning with the end of Byzantine rule there in the 7th century A.D. However, increasing variability in major element compositions of glass has been noted throughout late antiquity; most notably, the beginning of the 4th century A.D. sees the introduction, at sites throughout the Empire, of the significant compositional group known as HIMT (high-iron, -manganese, -titanium; all three of these elements are suggestive of the use of a less pure sand). This phenomenon has been attributed to a breakdown in trade caused by the gradually failing military and political institutions of the Roman Empire. Attempts at gauging the changing intensity of long-distance trade within the Roman Empire over time, for instance by counting the known shipwrecks of different periods, are perhaps a little haphazard, but tend to favor an economic decline beginning late in the 2nd century A.D., which is broadly consistent with this notion. There is, however, a rather glaring problem with the view of HIMT as symptomatic of the economic decline of late antiquity. This is the fact that, although its precise geographical origins currently remain a mystery, it is generally conjectured, without much dissent, to be of Egyptian manufacture. It is easy to see why a breakdown in trade should cause western

387 Picon and Vichy 2003, p. 18.
388 Shortland et al. 2006, p. 527.
390 e.g. Hopkins 1980, p. 106; Scheidel 2009, p. 15.
Europe to favor its own local production over imports; it is difficult to imagine why the same should favor Egyptian goods over Levantine equivalents.

Degryse and others, who favor the dispersed production hypothesis, note that the same period of crisis is also associated with the disappearance of those traits that they consider indicative of western primary production (neodymium isotope signatures, certain distinctive trace element combinations).\textsuperscript{392} What we actually see, in that case, is the collapse of the western primary glass industry as that half of the Empire was placed under more and more pressure, so that new Egyptian and Levantine centers (possibly using lower-quality raw materials) had to pick up the slack. Degryse’s view appears to be influenced by a teleological understanding of the fall of the Roman Empire: of course the situation was worse in the west than in the east during the 3\textsuperscript{rd} and 4\textsuperscript{th} centuries A.D.; after all, we know that Byzantium endured when Rome fell. This model would, as so much else in this field, benefit from serious scrutiny by professional archaeologists and historians, but it is an interesting starting point for future discussion, and makes an effort to show how our understanding of the organization of the glass industry is interconnected with our views of large-scale socioeconomic change.

**Further Questions**

Sourcing the raw materials of Roman glass is perhaps the broadest current question in the field, and has been the primary focus of this review, but it is not the only question that chemical analysis allows us to ask. The use of specialized materials and recipes,

\textsuperscript{392} Degryse 2014, p. 117.
particularly colorants, is another area to which archaeometry is naturally suited. Archaeometry’s suitability for investigating color and pigment is well known, particularly in wall painting. Glass provides a spectacular range of color to investigate, though archaeometrists (predictably, at this point) are not known for anything beyond identifying the material characteristics that give rise to color. Looking into how colors would have been experienced or why they were chosen might provide interesting common ground with more traditional archaeologists.\footnote{Jones 2004, p. 334.}

We might ask, for instance, what variations of more or less intense color can be produced by different quantities or mixtures of colorants, and whether any particular shade seems to have been targeted (perhaps in imitation of a certain precious stone or other natural source of inspiration – Pliny, *HN* 36.67, mentions sapphires and hyacinths). Colored glass has been the subject of less systematic archaeometric study than uncolored (that is, “naturally” colored) glass, because its more complex chemistry makes it difficult to incorporate into large-scale work that attempts to locate sand sources, but the possibility of gleaning information about production at the secondary level, when most colorants were probably added, should not be discarded. Ingredients that alter the physical properties of glass, particularly lead compounds that soften glass intended for carving, may also offer insight into the organization of production. The addition of these is not universal, so it is natural to ask when they were thought necessary, and what factors governed that decision.

The unique gold-based colorant used in the 4\textsuperscript{th} century A.D. Lycurgus Cup (see section 3) is an especially striking example of the use of unusual ingredients to confer specific properties on a glass. Archaeologists familiar with the object are doubtless
weary of sensationalizing headlines describing the goblet’s makers as “nanotechnology pioneers” or similar, but chemists are right to be astonished at the technical proficiency implied by its composition. It is likely that the Cup’s famed dichroic effect could only have been achieved using chemical reagents that are not otherwise attested for the Roman period (aqua regia, or some similarly potent solvent capable of dissolving metallic gold), coupled with fine control over the temperature and atmosphere of the furnace that was used to work the glass.\textsuperscript{394} Even by modern standards, it is a technically impressive piece, and comparable Roman-era dichroic glass is all but nonexistent. Only a handful of fragments of other vessels are known, and most of these exhibit far less striking changes in color.\textsuperscript{395} Most, like the Lycurgus Cup, are fragments from cage cups (though not so lavishly decorated), which has suggested to some authors that their optical properties might originally have been intended in service to their use as lamps, a known function of some cage-cups.\textsuperscript{396}

How it might have occurred to Roman glass artisans to combine gold with glass in the first place is unclear, though the 4\textsuperscript{th} century A.D. is perhaps one of the more likely periods in which one would expect to see experimentation of this kind. The same period is also known for Roman production of gold-glass, originally a Hellenistic technique that appears to have been relatively little-used in the intervening centuries, in which a design in gold leaf is “sandwiched” between two surfaces of colorless glass, fused together by heat.\textsuperscript{397} This is a period, then, in which artisans working in glass and gold are likely to have been in close proximity; they may even have been

\textsuperscript{394} Barber and Freestone 1990, pp. 42-43.
\textsuperscript{395} Harden 1987, p. 247.
\textsuperscript{396} Elsner 2013, p. 107; Lierke 2013, plate 31.
\textsuperscript{397} \textit{e.g.} Triantafyllidis 2002, p. 32 for Hellenistic examples from Rhodes; Howells 2013 for late antiquity.
the same people. The addition of metal to a glass melt would presumably have been familiar to them already, from the use of scrap bronze as a colorant in copper blue glasses.

Daniel Howells has perceptively noted that the makers of 4th century A.D. gold-glass were quite sparing in their use of gold, and that the use of the precious metal is not likely to have disqualified the Roman “middle class” from ownership of these artifacts.398 This is even more true of the Lycurgus Cup. To say that its precious metal content is not high understates the case somewhat; at 40 parts per million by weight, the entire goblet would contain approximately 28 milligrams of gold.399 At modern market prices, this minuscule amount would fetch a sum conveniently met by the change currently in the author’s pocket; a single Constantinian solidus would have contained enough gold to make over a hundred Lycurgus Cups. Other than the presence of colloidal metals, and a slightly elevated manganese level, the Cup’s chemical composition is perfectly ordinary, and it could have been made from much the same raw materials as any other glass of the period.400 In fact, the manganese content might even suggest the use of recycled cullet rather than fresh chunk glass.401 The Lycurgus Cup’s uniqueness clearly has nothing to do with the cost of materials; it is more likely that the technical knowledge involved in its creation was incredibly restricted. It may even have been regarded as a trade secret.

398 Howells 2013, pp. 117-118.
399 This is going by the Cup’s mass of 700g reported by its page on the British Museum’s website – in fact, the mass of the glass itself is probably lower since the stated figure seems to include the Cup’s (modern) silver-gilt fittings.
400 Barber and Freestone 1990.
401 The Lycurgus Cup’s reported MnO content of 0.5% by weight is in fact higher than the 0.4% generally taken to be indicative of deliberate addition (e.g. Schibille and Degryse 2013, p. 161), though it is difficult to see what purpose it would serve in this particular object.
Continuing the theme of color, it is well documented that Roman tastes, which initially favored brightly colored glasswares, came instead to prefer subdued or colorless ones during the second half of the 1st century A.D., and continued to do so throughout the High Imperial period. The reasons for that shift are the subject of far less discussion, however there is a fairly sensible answer. Pompeian artists seem to have had a certain fascination with glass, and a number of wall paintings depict colorless (or nearly so) glass vessels, often holding fruit or wine (see figure 5.1). It has been argued that the ability of colorless glass to display its contents was of special interest to them. If so, this interest doubtless extended to others beyond Roman painters. The change in the colors of glass that the Romans enjoyed, and hence the archaeometrically visible change in the materials used to make them, may reflect a change in the way consumers viewed and valued glass. Hellenistic glass was still a luxury good, and valuable in its own right. Elite consumers desired ostentatious colors, often imitating precious stones, that made the glass itself the center of attention. Roman blown glass objects, being mass-producible, and therefore much cheaper, were instead valued for their ability to showcase their (often brightly colored) contents in a

Figure 5.1: Wall painting from the House of Julia Felix, Pompeii, depicting a glass bowl filled with fruit. After Naumann-Steckner 1991, plate 24.

\[^{402}\text{Grose 1991, p. 13; Henderson 2013, p. 207. Note also Pliny’s comments (HN 36.67; see section 3) about the prestige of colorless glass.}\]

\[^{403}\text{Naumann-Steckner 1991, p. 98.}\]
way that their pottery equivalents could not, and so materials were chosen that emphasized this quality.

In a similar vein, it is broadly accepted that a shift occurred some time during the late Hellenistic or early Imperial period from the use of antimony compounds in producing colorless glass to the use of manganese compounds. Recognition of a distinction goes back at least to Sayre and Smith’s seminal 1961 study, though every author on the subject seems to have a different opinion on exactly when manganese was first used deliberately and when it began to predominate. However, I have yet to find a convincing explanation, or even any attempt at an explanation, as to what prompted the change. Indeed, in the rare instance when glasses made using the two different compounds are explicitly compared, some modern scholars seem to feel that the antimony-based compositions are actually superior, having a more “brilliant” appearance. Moreover it is not uncommon to find mixed compositions, where both elements are present in concentrations that appear deliberate (though at least some of these are doubtless the result of mixing recycled cullet). Brill, in fact, doubted that manganese was intended primarily as a decolorizing agent at all, at least in its use at 4th century A.D. Jalame, where many high-manganese samples were, in fact, strongly colored. He speculated that the Jalame glassmakers used manganese compounds to shift the “natural” blue-green hue of Roman glass further towards yellow-green. More recent literature, however, tends to accept the older view that manganese and

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404 Sayre and Smith 1961, p. 1825.
405 Arletti et al. 2008, p. 621.
406 e.g. Baxter et al. 2005, p. 60.
407 Brill 1988, p 277. Because of the way manganese and antimony function as decolorants (see section 2), fairly precise amounts are needed to produce truly colorless glass. Excessive manganese, for instance, often produces visible purple streaks in the glass.
antimony are simply two options for the production of colorless glass. A well-planned program of simple, non-invasive colorimetry and X-ray fluorescence spectrophotometry would go a long way towards comparing the performance of the two “decolorants,” and assessing patterns of their use.

The high lead content of the white glass used in the base disk of the Portland Vase, and in other cameo glasses of the Augustan period, is a less visually obvious example of modifying a basic glass composition. However, the rationale behind it is clear: like modern lead crystal, this Roman high-lead glass would have been significantly softer and easier to carve than a typical formulation.\textsuperscript{408} A similar addition, for a somewhat less extravagant purpose, was noted by Baxter, Cool, and Jackson as being specific to facet-cut beakers, within an assemblage of colorless Romano-British vessels of the first three centuries A.D.\textsuperscript{409} These modifications to the standard Roman soda-lime glass recipe could have been made at the level of secondary production; they therefore say little about the question of western primary glass production. However, they demonstrate that glass compositions could be adapted for the purpose at hand. This implies either the commercial availability of raw high-lead glass, meant specifically for carving, or that glassblowers could modify their raw materials themselves. Lead isotope analysis might turn up usable data on the nature and location of the geological lead source, further clarifying this question.

\textsuperscript{408} Whitehouse 1991, p. 28. The white glass of the Portland Vase’s body, interestingly, does not contain lead (Harden 1987, pp. 66-67); this is one of several reasons the base disk is generally thought not to be original, but added during repairs made in antiquity. Its date, however, is believed on stylistic grounds to be similar to that of the vase itself.
\textsuperscript{409} Baxter \textit{et al}. 2005, p. 54.
Finally, it is worth taking some time to consider those rare examples of Roman glass whose compositions are radically different from typical examples. Although soda-lime compositions, generally falling within a fairly narrow range, are overwhelmingly dominant throughout the Roman and into the early Byzantine periods, variability is never extinguished. Plant ash compositions, readily identifiable by their high levels of magnesium, potassium, and often phosphorus in the case of wood ash compositions, are rare and unusual, but far from unheard of. Ash glasses are known from Roman period sites at, for example, Augusta Praetoria (modern Aosta) in northwest Italy, and Fishbourne in Sussex, far from the Middle Eastern regions where the plant ash tradition persisted without interruption (and, in the case of Fishbourne, far even from the busy Mediterranean trade routes). A few samples from sites in Switzerland also exhibit intermediate magnesium and potassium concentrations that may have resulted from the recycling of an ash glass; the analysts, in this case, rejected the possibility, though their reasons for doing so are unclear.\(^{410}\) The Fishbourne example is an interesting one, as the ash composition seems to have been associated only with a specific ware type: emerald green bowls. Five examples of this type were analyzed, and all had the distinctive high magnesium levels of an ash glass.\(^{411}\) The association is curious, especially since the bowls themselves are not atypical for 1\(^{st}\) century A.D. Roman Britain, and do not immediately seem likely to be imports, though in view of the compositional data it may be wise to consider this an open question. Other possibilities (imported cullet or a local plant ash industry, in either case used specifically for this type of bowl) do not seem to make a great deal of sense. If it should prove possible in future to identify the species of plants used in

\(^{410}\) Arletti et al. 2008, p. 618.

\(^{411}\) Henderson 1996, p. 190.
these glass types, or perhaps identify the region where they grew based on strontium isotope analysis, more satisfying explanations might present themselves.412

Conclusion

Archaeometric glass studies are sharply limited by the availability of instruments, expertise, and funding. However, contrary to what a cursory survey of the literature might suggest, this is not the only or most important limitation to what can be accomplished by scientific techniques. Far more important is willingness to integrate, a readiness on the part of archaeologists to familiarize themselves with the principles of the physical sciences, and on the part of scientists to understand and contextualize their work in archaeologically meaningful terms. When these conditions are satisfied, the result is a unique line of evidence on ancient technology and economics that can reveal interesting (and, at times, unexpected) details about the production process. When they are not, the result is irritating minutiae, a passing curiosity to scholars and scientists alike.

Glass in particular is an interesting material to study archaeometrically because of the way glass artifacts are made. Like refined metals, glass can be made in one location and worked into its eventual form in another. The number of primary production locations also seems to have been very limited (though it is unclear just how limited). This means that glass carries information about choices made at two different stages of production. At primary production, these include which flux to use (almost invariably natron in the Roman period, despite the availability of alternatives), where

412 See Henderson 2013, pp. 36-42 for some general thoughts on the former possibility.
to gather sand, possibly whether to modify the sand, and possibly whether to enrich the sand with crushed shell or limestone (see section 4). At secondary production, there are choices relating to style that are the domain of traditional typological analysis, but also archaeometrically visible choices relating to the use of recycled material, colorants, and other specialized ingredients. The resulting complex chemical profile can obscure the signature of geological source materials; a great deal of archaeometric work, including most of that surveyed in section 4, has seen this as a limitation to be overcome, using raw and uncolored glass where possible so as to facilitate an exclusive focus on the primary stage (and with good reason, given the objectives of those studies). However, these same complications also mean that chemical data can be interpreted in light of regional, as well as Empire-wide trends. Work on understanding the full significance of archaeological glass chemistry is still only just beginning.
Section 6: Conclusions

This review has aimed to present recent developments in the archaeometric analysis of Roman glass in their context as contributions to the study of Roman civilization, and to highlight opportunities for future development in areas of archaeological interest. In addition, I have tried to stress the importance of truly interdisciplinary cooperation, a commitment by archaeologists and archaeometrists to work together closely in developing their research questions and interpreting the results of experiments, rather than unthinking “multidisciplinary” juxtaposition of chemical characterization with traditional archaeological data that makes no serious effort to establish relationships between the two. Roman glass is particularly interesting from this perspective, first because glass is a chemically complex material that contains information about multiple natural substances and stages of production in its composition, and second because of the Imperial period’s status as a time of major innovation and intensification in the glass industry. The better archaeologists are acquainted with the complexities of glass as a material, the better placed we will be to develop new questions that exploit the sources of information archaeometric techniques can give us.

Glass is a unique material in the classical Mediterranean, which presented unique challenges and opportunities to artisans. Its lack of long-range molecular order, as well as giving it transparency or translucency, results in a prolonged, continuous transition from solid to liquid over a range of temperatures, rather than the discrete melting point observed in typical “crystalline” solids. The pliable, semi-liquid nature of hot glass dictates the way it can be shaped. Although the possibilities were not
fully exploited until the advent of blown glass at the end of the Hellenistic period, even the earliest vessel glass traditions created some spectacular core-formed pieces by combining rods of hot glass in different colors. The structure of glass dictates how we are able to analyze it as well, since the combination of the different components of a glass batch into a covalently bonded network structure makes it impossible to separately characterize the sand, flux, and colorants, as we might isolate and characterize temper in pottery. Only some glass compositions are viable; others will corrode, devitrify, or simply be unworkable at any realistic temperature. Within those ranges, though, many alterations are possible to produce the wide range of colors observed in ancient glasses, or occasionally to alter its working properties. Understanding the varieties of natural materials that can potentially be used allows us to frame questions in terms of resource exploitation. We can examine, for instance, why certain colorants or fluxes were chosen (or, for that matter, eschewed) in different regions and periods.

The archaeometric analysis of glass is still a relatively young field of study. Important questions about the origins of major compositional groups have yet to be resolved, and recently developed methods in isotope studies have yet to become widely accepted as part of standard archaeological practice. Straightforward forms of compositional analysis yield the surprising result that most uncolored Roman glass was probably made using a highly restricted range of raw materials, and therefore that primary production probably occurred in a restricted geographical region (colored and decolorized glasses being, most likely, variations made at the secondary level). Recent work, however, has indicated that the situation may be more complicated. The historical record supports the idea that the northern Levant was central to the
early Roman glass industry, and the vast majority of secure archaeological evidence for primary production also points toward the importance of Levantine and Egyptian centers. Without the recent chemical evidence, we would be almost forced to dismiss Pliny’s description of primary glassmaking in Italy as a mistake or a misunderstanding. Taking into account the work of the last fifteen years, it is an open question how widespread primary glassmaking was in the Roman Empire. It remains to be seen how our ideas will change as neodymium isotope analyses become more widespread.

Archaeologists, for our part, must make an effort to understand how samples from our sites may fit into the wider picture described by these chemical analyses, so that we can make intelligent choices about the material we offer up for study, particularly for destructive techniques. We must, of course, balance the needs of our analytical methods with the preservation of antiquities for future study, but experience tells us that a small sample set can be as bad as no sample set at all. Developing an accurate impression of compositional variety at any given site may demand that we analyze hundreds of sherds, and ideally there should be good representation in the sample set of different phases of the site, different colors, and different shapes (particularly if, for instance, both blown and cast types are present, as the demands of different techniques may have prompted modification of the raw glass by individual workshops), though obviously sample selection strategies should be sensitive to the research question at hand. Here the liberal use of non-invasive techniques can be invaluable, not only because they give us a way to characterize huge numbers of finds, but because they can help us gain a basic understanding of the variability of our finds’ chemistry, and thus form representative sample sets for more comprehensive
investigation, particularly isotope studies. This kind of strategy is already being
employed productively at late antique sites on Cyprus, and will hopefully become
more widespread as time goes on.413

The historical context of the Roman glass industry is also interesting to think about.
The traditions of glass manufacture in the classical Mediterranean made use of
specialized knowledge that had been available since the Late Bronze Age or even
longer, like colorants based on cobalt ores that produced deep blue glasses, or the
ripple and feather decorations associated with core-forming. It was, for a long time,
an extremely conservative tradition. The first century of the Imperial Roman period,
however, corresponds with a time of extraordinary innovation. It is simplistic to give
all the credit to the Roman Empire, or to the ideal conditions for innovation created
by the pax Romana, for the first glassblowers were likely natives of Judaea, working
during the tumultuous period of the establishment of the pro-Roman Herodian
dynasty. However, the Roman Empire certainly seems to have provided a suitable
environment for the propagation and perfection of the new technique. Refinements
such as iron blowpipes, and the very large glass vessels that they make possible,
probably occurred for the first time in northern Italy. The extravagant, skill-
demanding cameo glasses of the Augustan period are likely Italian as well. Pliny the
Elder, writing in the first century A.D., appears to view glass, and the variety of
colors and properties that can be created by manipulating its composition, as a prime
example of human, particularly Roman, ingenuity, perhaps even a manifestation of
human mastery over nature. The Roman Empire had a tendency to concentrate

413 Ceglia 2014, pp. 89-91.
wealth and expertise in Italy, and the glass industry was a major beneficiary of this effect.

In addition to all this, if commonly held beliefs about the centralization of primary glass production in the Roman Levant are ultimately upheld, we are faced with an industry whose operation must have entailed a fairly sophisticated infrastructure, and a great degree of interdependence between far-flung regions. We know independently that primary glass production using locally available resources did occur in western Europe during both the High Middle Ages and (to a lesser extent) the Final Bronze Age; if it truly did not during the Roman period, this absence demands explanation. Furthermore, if the Roman west did produce raw glass, as some evidence suggests it may have, it is curious that it apparently did so using mostly Egyptian natron, not local plant ash. Either Levantine raw glass, Egyptian natron, or both must have been available very cheaply and in bulk quantities in the west. As we have seen, the solubility of natron in water makes it unlikely that we will ever confirm its presence in the cargo of a shipwreck, though glass was clearly shipped in huge amounts, as the Ouest Embiez wreck makes clear. The ready availability of these eastern commodities in the west have been a result of the uniquely low-risk conditions for maritime shipping created by the political and economic institutions of the Roman Empire.\textsuperscript{414} However, making conclusions of this kind demands that we give some attention to the circumstances of late antiquity as well. What are the reasons for the importance of the HIMT group, which is usually believed to represent Egyptian production, beginning in the 4th century A.D.? Is the persistence into the early Mediaeval period of compositional groups typical of earlier centuries the result of

\textsuperscript{414} Scheidel 2009.
recycling alone, or did the glass trade remain fairly vigorous after the “fall” of the western Empire?

Color chemistry is also underexplored at present. This is partly because a great deal of the interesting and systematic work of the last two decades has focused on defining major compositional groups, and therefore has looked mainly at uncolored glass (which, in any case, is extremely common in the Roman period), to avoid the complications inherent in dealing with glass modified at the secondary level. The basic palette of colors available to ancient glassmakers is well-established, and in many cases the necessary ingredients would have been readily available almost anywhere in the Roman period (blue-green glasses, for instance, were probably made with scrap bronze). However, some colorants, such as manganese (probably derived from pyrolusite) and lead antimonate (a byproduct of the extraction of silver from galena) may have been more geographically restricted, and here isotope studies might allow us to pin down specific sources. Different ingredients that produce the same, or similar, colors are also worth investigating, such as manganese and antimony, both of which can be used to make colorless glass. Since colorants are likely to have been added to glass at the secondary level in the Roman period, variation in the use of different colorants between sites, and between artifact types (particularly if this can be linked to imitation of other, perhaps more prestigious, materials, such as rock crystal in the case of colorless glass), could be an interesting avenue to explore.

Further progress in using chemical techniques to answer archaeological questions will require the active participation of archaeologists in articulating those questions, and interpreting the results of experiments. Archaeometrists can produce innovative and
important work with only the vaguest of direct assistance from archaeologists, but a lack of familiarity with archaeologists’ priorities and ways of thinking, coupled with simple interdisciplinary rivalry, make integrating that work into archaeological debates a much less straightforward matter. Chemical evidence is perfectly capable of making substantial contributions to the way we view the Roman economy, and Roman attitudes to industry and technology in the Imperial period, but only if we, as archaeologists, are willing to engage with it and understand it on its own terms. The difference between a Roman Empire where raw glass is only made in the Levant and Egypt, and a Roman Empire where raw glass is made everywhere, is surely not an insignificant one. The methods of chemical analyses themselves certainly deserve further study, but the way we make use of those analyses deserves even more.

Archaeometry is sometimes characterized as a completely different, foreign way of understanding the past, a way based on the supposed objectivity of the scientific method, as opposed to the subjectivity and intuition of more theoretical brands of the discipline. Proponents of the “New Archaeology” of the 1960s and 1970s are often seen as embracing this objectivity out of a desire to frame archaeology as a science; more recent scholars have railed against it, ridiculing the “scientific” worldview as empiricist and determinist. Either reaction is missing the point. Archaeology is, fundamentally, about using physical objects to derive information about cultural processes. We study a pot; we infer a potter. Different schools of archaeological thought will dispute what, exactly, we can say about the potter on the basis of our knowledge about the pot, but the point is always that something of human importance can be learned from the observable traits of an object. Archaeometry does not change

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this, and although it has been associated more strongly with some theoretical paradigms than others, it does not (or, at least, should not) inherently imply one or another. What archaeometry does is expand our perception of objects and environments beyond what our own senses, unaided, can allow. What we do with the information these artificial “senses” grant is up to us.
Glossary of Terms

*Accuracy.* In statistics, the deviation of measurements from a hypothetical “true” value for the parameter being measured. Contrast *precision.*

*Analyte.* The chemical species targeted for measurement in an analysis.

*Annealing.* The process by which finished glass objects are held just above the material’s glass transition temperature (about 500-600 °C in most soda-lime glass) for several hours or days, in order to allow time for internal mechanical stresses to relax. If objects are not properly annealed, these lingering stresses can weaken or crack the glass.

*Archaeometry.* Applications of analytical techniques and expertise derived from the physical sciences, principally chemistry, to the study of archaeological materials.

*Atomic absorption spectroscopy or AAS.* Techniques that establish the elemental composition of samples by atomizing them in a flame, and measuring the absorption of light at specific wavelengths as it passes through the flame. Generally among the cheaper techniques available, and achieves good analytical accuracy and precision, but destroys the sample, and will only measure elements specified in advance.

*Atomic emission spectroscopy or AES.* Similar to atomic absorption spectroscopy, but measures light given off by excited atoms in the flame rather than light absorbed. Superior sample turnover to AAS, measures more comprehensive spectra, and reduces interference, but has higher detection limits.

*Colorless glass.* Glass that contains chemicals specifically added to reduce or eliminate the appearance of its “natural” color, such as manganese oxide. Contrast *uncolored glass.*

*Core-forming.* A technique for creating glass vessels by building up layers of glass, either as glass dust or coiled rods, around a clay core, which is scraped out of the finished vessel.
Cullet. Crushed or broken glass, especially recycled, used as a raw material or colorant in production of glass vessels.

Cracking off. The act of breaking a blown glass vessel off the end of the blow-pipe, usually after scoring a line around the rim with a metal tool to ensure a clean break. Some Roman vessels simply leave the cracked off rim, but most finish the rim in some way.

Crystalline solid. A solid that is characterized by long-ranging symmetry and periodicity on a molecular scale. Contrast glassy solid.

Energy-dispersive X-ray spectroscopy, EDS or EDX. A detection technique used in conjunction with scanning electron microscopy, which measures the energy of X-rays given off by atoms struck by the electron beam to determine the elemental composition of the sample. Can be finely targeted to characterize inclusions or decorative features independently, but only characterizes the surface of a sample, and while not technically destructive, normally requires invasive sample preparation.

Flux. In metallurgy and related fields, a component added to a mixture with the aim of reducing its melting point and viscosity. Fluxes used in glassmaking include natron and the ashes of certain plants.

Frit. Glass dust or powder, used as a raw material or a colorant in production of glass vessels, or an intermediate stage in some methods for producing raw glass, at which the raw materials have reacted, but not yet fused into a vitreous mass, and are still sandy in texture.

Gather. The molten glass that is collected on the end of a blow-pipe when it is inserted into a glass furnace, or the act of collecting this.

Glassy solid. A solid that is characterized by the absence of long-ranging structural order on a molecular scale. Substances can be termed “glassy” regardless of their
chemical composition, and the term can encompass materials like plastics as well as “glasses” in the traditional sense. Contrast crystalline solid.

Glass transition temperature \((T_G)\). The temperature at which atoms or molecules in a glassy solid have sufficient energy to rearrange themselves relative to each other. Above \(T_G\), it is possible for internal mechanical stresses in the material to relax.

Halophyte. A plant that grows best in salty water. The ashes of certain halophytes, notably those of the genera Salsola and Salicornia, are particularly good fluxes for glassmaking.

Isotopes. Atoms that have the same number of protons, and are therefore by definition the same element, but different numbers of neutrons, and therefore different atomic weights.

Mass spectrometry or MS. Any of a variety of methods that use magnetic fields to sort atoms or molecules in a sample by their mass. Mass spectrometry is commonly used for analyzing the structure of complex organic molecules, and is also important for analytical strategies that involve investigating isotope ratios, most notably radiocarbon dating.

Natron or nitrum. A mixture of sodium salts, mainly carbonates and bicarbonates, used in the ancient world for making soaps and detergents, in certain medicines, as a desiccant, and as a flux in glassmaking. Obtained mainly from dry lake beds in Egypt, particularly the Wadi Natrun area, which derives its name from the substance.

Neutron activation analysis or NAA. A method for analyzing the elemental composition of samples by irradiating them in a nuclear reactor, then measuring the secondary radiation given off by radioactive decay in the sample during subsequent days, weeks, or months.

Percentage by weight \((\text{wt\%})\). The portion of a sample’s mass that is made up by a particular chemical component of the sample. Contrast molar percentage \((\text{mol\%})\), which expresses the number of the sample’s atoms or molecules that belong to a
particular chemical component, or percentage by volume (vol%), which expresses how much of a liquid or gaseous sample’s volume is made up by a particular chemical component. Elemental analyses of glass and pottery, by convention, report results in percentage by weight.

*Pontil or punty.* A common glassblowing tool; a metal rod that is attached to the bottom of a blown glass vessel using a blob of hot glass before the vessel is cracked off the blow-pipe. The punty acts as a handle during manipulations of the top part of the vessel, such as flaring open the mouth or finishing the rim. Use of a punty leaves a visible “scar” on the base of the vessel at the point of attachment, which can be removed by sanding, but in ancient glass production is often left.

*Precision.* In statistics, the degree of agreement between replicate measurements of a single parameter. Contrast *accuracy.*

*Primary glass production.* The production of “raw” glass by fusing naturally occurring materials such as sand and natron. Contrast *secondary glass production.*

*Provenance.* In archaeology and art history, an artifact’s history since its modern discovery, including ownership, sale, and incorporation into collections. In archaeometry and geochemistry, often used to mean the geographical origin of the raw materials that were used to make an object. See also *provenience.* Owing to the inconsistent meaning of this term across disciplines, it will be avoided in this review.

*Provenience.* In archaeology, the context in which an artifact was found, including stratigraphic position and associated artifacts or features; its find-spot. In archaeometry, occasionally used with the same sense as *provenance.* Owing to the inconsistent meaning of this term across disciplines, it will be avoided in this review.

*Sagging or slumping.* A technique for shaping glass, in which a flat sheet of glass is heated in a kiln over an open or inverted mold, so that it slumps over the mold, or sags into it.
Scanning electron microscopy or SEM. An imaging technique that fires a beam of electrons at a sample, and builds up a relief image of its surface by measuring the way the electrons scatter. Closely associated with energy-dispersive and wavelength-dispersive X-ray spectroscopy.

Secondary glass production. The production of vessels and other objects from pre-prepared lumps or chips of raw or recycled glass. Contrast primary glass production.

Soda-lime-silica glass. A glass whose major chemical components are silica (silicon dioxide, SiO$_2$), soda (sodium oxide, Na$_2$O), and lime (calcium oxide, CaO). Dominant in the Hellenistic, Roman, and Byzantine periods, and common in modern industry, but rare in all other historical periods.

Trace elements. Elements that make up less than 0.1% of a sample. The presence and relative abundance of trace elements in natural materials may “carry over” to archaeological materials made from them, and therefore may serve as a chemical “fingerprint,” identifying the region the raw materials came from.

Uncolored glass. Glass that does not contain any materials specifically added to alter its color. The “natural” color of Roman glass is typically a faint translucent blue-green. Contrast colorless glass.

Viscosity. The resistance of a substance to flow, the “thickness” of a liquid. Most substances experience a major step change in viscosity upon reaching a clearly definable melting point; glasses instead decrease their viscosity slowly over a broad temperature range.

Wavelength-dispersive X-ray spectroscopy, WDS or WDX. A technique similar to energy-dispersive X-ray spectroscopy that measures the wavelength of X-ray emissions rather than their energy. Analysis times are longer, and only elements specified in advance will be measured, but interferences are significantly reduced.

X-ray fluorescence analysis, or XRF. A method for analyzing the elemental composition of samples by bombarding them with high-energy X-rays, then
measuring the lower-energy secondary X-rays given off as excited electrons relax to their ground states.
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