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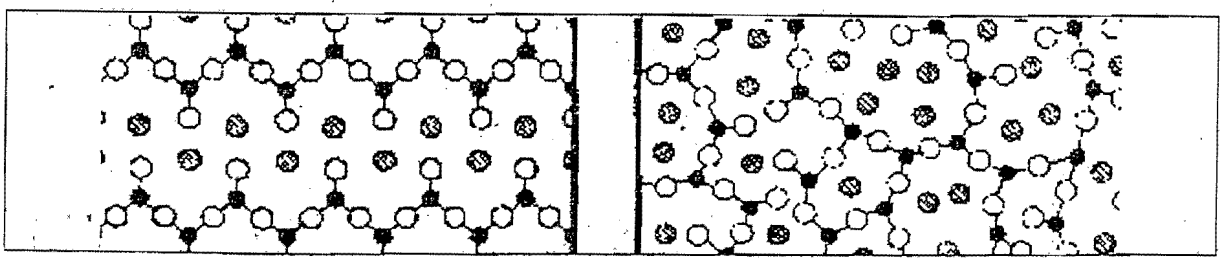
The MARGARETOLOGIST

GLASS



A diagram of the structure of a crystalline substance (on the left) and of glass (on the right). The black dots are silicon, the open dots oxygen and the shaded dots sodium (after Brill 1962:133).

GLASS ANALYSIS

Fig. 2 Glass factory of the 16th century from Biringuccio's *Pyrotechnia* (Smith and Gnudi 1943:133).

and the ANALYSIS OF INDO-PACIFIC BEADS

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Through the Eye of a Needle

The last year has been exciting. It included appearances in Toronto, Denver, Chicago and Minneapolis, a most satisfying Bead Expo '98 and continuing consulting with the American Museum of Natural History, New York on St. Catherines, Georgia. I was in Ghana for three months and on to the Berenike, Egypt, excavation for one. I got very sick the last month in Ghana and remained so in Egypt. I have slowly recovered since (the doctors never did figure out what it was). Thanks to all who expressed their concerns. I am much better now.

A highlight of this year has been the analyses of 20 Indo-Pacific bead samples by Ron Hancock of the University of Toronto, to whom I am deeply grateful. This program has answered several questions regarding this crucial bead industry. It is the key finding presented in this issue. To introduce it, I enlarged on the topics of glass and glass analyses. I hope you find it stimulating.

The last issue (Seed Beads) has been one of the best-received numbers to date. This is due to the tremendous interest in beading and the desire to understand the complexities of the smallest beads. The success of Bead Expo '98 and the popularity of the Seed Bead Gallery on the **thebeadsite.com** are further proof of this, if any is needed.

Our web site, **thebeadsite.com**, just keeps booming. Because of it, I can present all the analyses made of Indo-Pacific beads (this issue has the new ones in Table 2). To access them go to **www.thebeadsite.com**. From the home page go to **Galleries**, then to **Color Plates for the Margaretologist**, then to the **version** appropriate for your browser. If you absolutely *can't* get on the Internet and absolutely *must* have copies of these tables, let me know.

Happy surfing!

CALENDAR

⇒ **15-19 June: Consulting at American Museum of Natural History, NYC, St. Catherine's' GA.**

⇒ **19 October – 5 November: Bead and Art Tour of India; stay in India for more research**

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The Margret Carey "Gotcha" Award has been extended to The Bead Site. She wins again. Corrections for 10(2).

Page/Column/Paragraph/Line

2/1/2/4 identify to identity
4/2/3/12 cassock to hassock
6/1/2/2 bead to beads
7/1/3/8 cm to mm
9/1/2/4 beads to bead
10/2/3/3 ordianry to ordinary
11/1/3/6 color lined to color-lined
13/1/5/2 Libraire to Librairie
14/1/1/7 Indonesia to Indonesia,

Glass and Glass Analysis

The world just wouldn't be the same without glass. There would be no windows, bottles or porcelain bathroom fixtures, not to mention televisions or light bulbs. And where would beads be?

Glass is so commonplace that we call many objects by that name – spectacles, mirrors, loupes and tumblers. Yet the nature of glass is a matter of scientific debate and hardly perceived by most people.

Glass is an odd duck. It is not a strictly material, but a state of matter, on par with solids, liquids, gasses and plasmas. It is similar to solids because it is firm, but also to liquids, because it lacks a crystalline structure (Fig. 1).

Let's compare glass to more common states of matter, using water as an example. When the temperature is over 100° C water is a gas called steam. The H_2O molecules are very excited (have high kinetic energy), move around rapidly and fill any container. When the temperature drops below that point steam condenses into a liquid and gathers at the bottom of a container, filling only a discrete volume. The molecules still have considerable kinetic energy and slip and slide around each other. Water is not very viscous (heavyweight oil and molasses are more viscous), so it flows easily.

When the temperature drops below 0° C. water forms ice crystals. The molecules are bound to together and no longer move around.[1] Ice is rigid; it is a solid.

Glass is firm, but highly viscous rather than strictly rigid. It has no crystalline structure but a lattice or network of molecules. It is thus like a liquid, but for practical purposes resembles a solid. It is sometimes called an "under-cooled" liquid. Additionally, glass does not have a definite melting point. It becomes more or less viscous slowly, without a sudden change in phase at a precise temperature.

The American Society for Testing and Materials (1979:294-5) defines glass as:

> An inorganic product of fusion which has cooled to a rigid condition without crystallizing.
>
> Glass is typically hard and brittle and has a conchcoidal fracture. It may be colorless or colored, and transparent to opaque. Masses or bodies of glass may be made colored, transparent, or opaque by the presence of dissolved, amorphous or crystalline material.

Many solids can be made glassy if melted and cooled quickly enough to prevent recrystallization. Since the 1960s, metallic glasses have become important materials. Razor blades and tape recorder heads were early uses, and other applications are being developed rapidly.

The precise structure of glass is under debate. Some liken it to polymers (long strings of molecules) that characterize plastics. Others believe it is composed of submicroscopic distorted crystals that form a random lattice. It can be thought of as an irregular network that can enclose foreign atoms or molecules (Fig. 1).

In everyday speech, and from hereon in this issue, the word "glass" is not used to designate a state of matter but to refer to a particular mixture of oxides. This is "commercial glass," the glass of everyday experience.

The Glassmaking Oxides

Glass is usually composed of three types of oxides, elements combined with oxygen, the most common molecules. Some are called simply iron oxide or lead oxide. Several are named by changing the ending of the element to -a or -ia. Thus, the oxide of silicon is silica, of aluminum alu-

[1] Their kinetic energy now only allows them to vibrate, as do all substances until absolute zero (ca. -273° C) is reached.

mina, of sodium soda and so on. Some have special names -- potash for potassium oxide and lime for calcium oxide.

Some oxides are "network formers" that create glass by themselves. They have atoms surrounded by four oxygen atoms and can form chains and networks in random fashion. Of these, silicon is by far the most important. Next to oxygen, silicon is the most common element in the Earth's crust, accounting for 27.6% of the atoms and 59% of its weight. Boron is the other important network former.

A second group of oxides are "network modifiers." The central atoms are larger than those of network formers and must be surrounded by more oxygen atoms. They do not become glassy by themselves. but when melted with network formers enter the glass composition. They include such critical ingredients as soda, potash, magnesia and lime.

A third group is "intermediary." Again, they do not form glass alone, but become part of the network when fused with a network former. Alumina is such an oxide, as is lead in heavy lead glass.

Each glassmaking oxide plays a role in making glass. Silica (usually as sand) melts at a temperature (1430° C) too high for ancient furnaces to achieve.[2] To lower its melting point a flux, usually an alkali (soda and/or potash) is added, obtained from alkaline deposits (Wadi Natron, the Dead Sea), soil efflorescence or plant ashes. Pure silica-soda is soluble in water ("water glass") and unsuitable for most applications. Lime prevents this. This seems not to have been known to ancient glassmakers, who added lime accidentally as shells or limestone impurities in the sand (Turner 1956a: 45-6T).

Each glassmaking oxide contributes to the characteristics of the finished glass. Fig. 3 (adapted from Scholes and Greene 1975:38) gives an idea of these properties. The three major ingredients of soda-lime glass are drawn at 120° to each other. At the lower right, silica gives glass its viscosity and vitreous character and retards its expansion under heat. To the lower left, soda lessens viscosity, promotes thermal expansion and makes glass prone to attack by water. At the top, lime prevents solubility in water and contributes to the tendency to crystallize or devitrify. Other glassmaking oxides are arranged in approximate relative positions. As the original authors noted, this scheme is oversimplified since no clear-cut division between the ingredients can be drawn. Yet is it a useful schematic representation of the origins of properties.

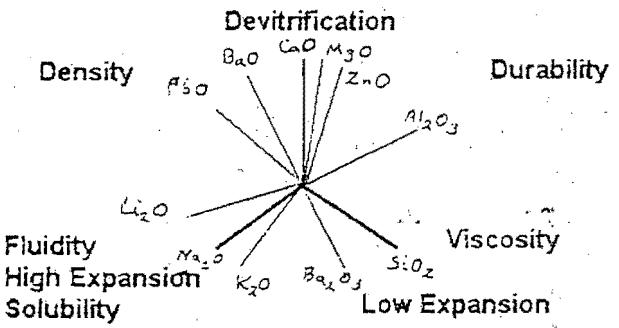


Fig. 3. See above for details.

Making Glass

There are natural glasses created by volcanoes (obsidian, pumice), meteorites (tektites), lightening (fulgurates) and intense fires that can even form glass from the silica in plants. While ancient people used natural glasses (especially obsidian for blades and other tools), there is no evidence that they employed any as a raw material in the manner of glass.

Glassmaking is a ceramic art, ceramics being the altering of earthy material by applying heat. Clay and steatite (soapstone) were the first ceramics.

The first artificial ceramic was faience, appearing in the Nile Valley about 5400

[2] That maximum was probably around 1100° C (Besborodov 1951; Turner 1954a).

years ago. Faience has a core of (usually) quartz particles melted only enough to adhere where they touch (sintered) and an exterior glaze, a true glass. As an independent synthetic material, glass was a technological advance made in Mesopotamia (modern Iraq) some 4500 years ago.

Glassmaking requires several steps. Sand (including the lime) and alkalies are crushed as finely as possible. Today the alkalies are washed, but the phosphorus in most ancient glasses indicates that this was not often done. These are put into a furnace (sometimes with colorants) and heated to about 750° C for several hours or days while being stirred (Fig. 4). The ingredients sinter and the resulting opaque, unpromising material is called "frit." Frit was sometimes repeatedly quenched in water to skim off impurities. It is then powdered and mixed with glass called "cullet" and perhaps colorants The whole is heated again, to 1050° or 1100° C, until it melts into molten glass (Fig. 5).

Other Glass Ingredients

Molten silicate glass is a universal solvent of oxides. It will dissolve water and gasses, though their volatility at high temperatures means that only small amounts are included in most glass. Glass will leach out alumina, iron oxide and other oxides from the clay of the crucibles and furnace. A complete list of all glass constituents, especially in older glasses made with impure components, can be nearly as long as the periodic table itself.

Other ingredients in glass are purposely added. These include those used for fining, opacifying and coloring the glass.

Fining agents remove bubbles. For soda-lime glass, arsenic and antimony are used. Both work similarly; arsenic is the example used here. Large bubbles, 1.0 mm or so in diameter, rise quickly in glass and can be driven off by a couple of hours of heat. Small ones ("seed") rise slower, and those of 0.01 mm take as long as a year and a half to rise as little as a meter.

Added in the trivalent (As_2O_3) form, arsenic converts to the pentavalent state (As_4O_{10}) as the batch is heated, absorbing oxygen. At maximum temperature, it slowly reverts to As_2O_3, releasing oxygen. Since the freed gas cannot easily form new bubbles, it joins small bubbles in the batch, enlarging them and causing them to rise and escape. As the glass cools, some As_2O_3 converts to As_4O_{10}, absorbing more of the remaining oxygen (Scholes and Greene 1975:216-20).

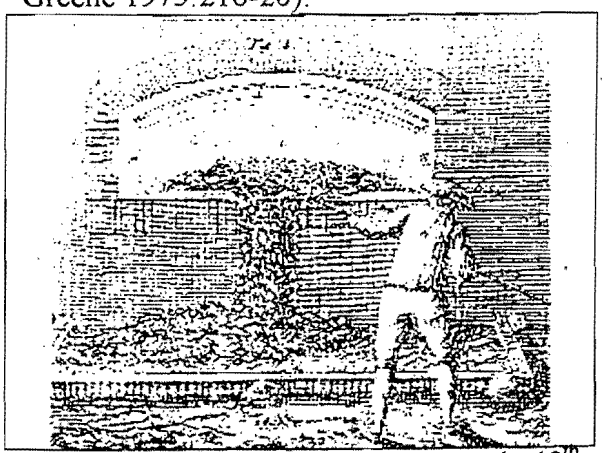


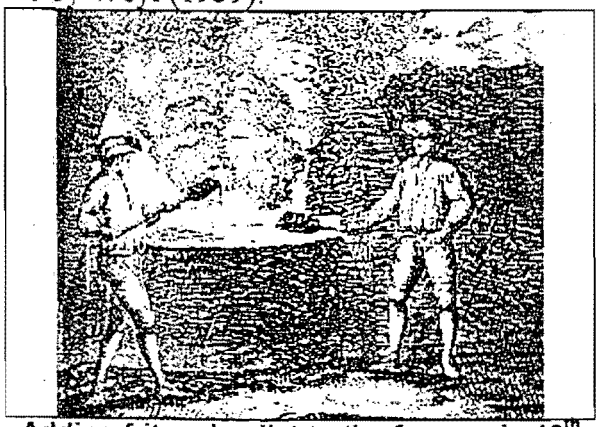
Fig. 4 removing frit from the furnace in 18th century France (Gillispie 1959 pl. 220).

Glass is normally transparent or translucent. Masses of bubbles or other impurities opacify glass, as do incomplete vitrification or devirification due to the presence of crystalline structures.. Antimony was used as an opacifier all but exclusively until about the first century AD[3], after which tin dominated. Phosphates (often as bone ash) came into use in the late 17th century, arsenic in the 18th century and the now common fluorides in the 19th century (Turner and Rooksby 1959; Henderson 1985:285-6).

The colors imparted to glass are a complex study. Many ingredients color glass

[3] Red glass was rendered opaque by the suspended copper particles that imparted the color.

and most colors can be made more than one way. The nature of the furnace, whether open, oxygenated or muffled (oxygen-starved) alters the final color. So does the fuel used, other oxides present, the amount of oxide used and the state (valence) of the oxide. Colorants may be added as unrefined ores, metals, frit or glass (cullet). The best work on colorants is by Weyl (1959).



Adding frit and cullet to the furnace in 18th century France (Gillispie 1959: pl. 222, 2).

When glass is made, it is usually green, called "bottle-green," as it is the color of cheap bottles. It is due to the universal impurity of iron, but even that is not simple. Ferrous iron (FeO) produces a yellow color, while ferric (Fe_2O_3) makes blue. Combined, they form green shades (Biek and Bayley 1979:14-5). It is extremely difficult to remove. Look edge-on at a modern "clear" pane of glass and note the color that is still present.

The proper applications of two anciently known metals, iron and copper, produce a wide range of colors. Two others were long used to color glass. Cobalt is a strong colorant that imparts a rich blue in small quantities. Manganese in small amounts yields pink. When suitably controlled it cancels out bottle-green, forming clear glass, giving it the nickname "glassmaker's soap." In higher concentrations, it makes a violet color and in still larger amounts a very dark or "black" glass. Large amounts of iron are also used to make "black" (actually deep green).

Modern chemistry has identified the elements that make up the universe. As each metal was identified, it was tried in glass, at least experimentally. Some elements unknown to the ancients have become important glass colorants. These include uranium (giving greens, yellows and orange), selenium (pinks, reds and the most common modern "glassmakers' soap") and cadmium (as cadmium sulfide), yielding a bright yellow.

Glass Analysis

Given that glass has so many constituents and a wide choice among possible ingredients, knowing the components of glass can tell us something about its origin, background, date or other useful information. At least that is the hope. In practice, glass analysis is an expensive proposition, either or both in time and money. Knowing the makeup of a piece of glass is only part of the story; it is also essential to interpret the information correctly.

The pioneer glass analysis was by the German chemist Martin Heinrich Klaproth, the discoverer of uranium, titanium and zirconium. He was interested in the colorants of some Roman mosaics from Capri and devised a way to analyze the samples, which he published in 1798. Some of his methods and interpretations were ahead of his time (he reasoned that different states of an element can make different colors), while others seem oddly lacking. He did not test for alkalies, but this was before sodium and potassium were identified as separate elements.

The chemical method (or "wet analysis") he used became the basis for most glass analyses until recently. It is a technique requiring many steps: powdering the sample and washing, heating and treating the decreasing residue with chemicals known

to react in certain ways with various elements. A detailed description of his work is in Caley (1962:13-15). It was not for half a century that glass analyses of higher quality were performed.

When vaporized and illuminated, elements will emit characteristic colors. Most high school chemistry students remember putting a powder onto the tip of a platinum wire and placing it into a flame to observe the color. Early in this century, arc spectrographs using an electric arc that simultaneously volatized and illuminated the substances tested were in use. Diffraction gratings separate the colors emitted. However, only relative amounts of elements could be determined at first, though this has been improved. The method is as destructive as wet analysis.

The introductions of more sophisticated techniques have proven valuable. X-ray fluorescence needs either large or powdered samples and examines only the surface of an object, a problem if there is any corrosion. A refinement of this method, the electron microprobe, analyzes only very tiny areas, and thus records variations in glass, which is not homogeneous. (For these older methods see Smith 1963.)

Still newer methods have been developed. Neutron activation bombards the sample, making the elements radioactive. They can be determined as they decay (many elements have very short half-lives). The PlasmaQuad removes a tiny sample with a laser and determines its makeup via mass spectrometry.

Yet with all this technical wizardry problems persist. Results are given in percentage of weights and differ if elements or oxides are reported. Not all elements are always reported because they were not all looked for. Errors mean that the totals rarely add up to 100%. If they do, silica was likely determined by adding up the other oxides and subtracting from 100%. Different results may come from different or even the same laboratory because of calibration errors or because glass is not homogeneous. Sometimes closely allied groups (iron and aluminum, soda and potash) are not separated. There is no general agreement on which oxides of a given metal are present, for example MnO or Mn_2O_3 (Weyl 1959:121).

Despite these obstacles, glass analyses, especially those done with the newer methods, hold out great promise as tools for understanding the history and significance of glass and glass beads. However, the proper interpretation of the results is crucial in reaching sensible conclusions.

The Why and How of Glass Analyses

Analyses of glass and glass beads have been done for different motives. Many seem to be done simply out of curiosity, perhaps looking for a key ingredient (usually colorants, alkalies or lead) or just to see what is in the glass. In these cases, interpretations are usually weak. (Sometimes it was not even recognized that clay or shell beads were included with the analyses of glass beads.)

There is nothing wrong in such analyses. In time, someone comes along and collects them, interprets them and draws conclusions. This has not yet been done for beads, but has been done for glass. The most valuable such summary is by Turner (especially 1956a, b, c[4]), unfortunately never published in book form. Caley (1962) is less informative, but still useful.

Another approach is to formulate a problem that can be answered by analyses, including previously published ones. This holds out more promise than the publishing of only a few analyses at a time, and has been used successfully in several

[4] These are three of six papers published in this journal from 1954 to 1959. Not all are cited here, but all are listed in the reference section.

cases. Some of those with the broadest implications are considered here.

The earliest was done for Chinese glasses, including many beads (Ritchie 1937, Seligman and Beck 1938). It confirmed the heavy lead content of early Chinese glass and revealed a surprising barium constituent. It was done by arc spectrometry, so that precise percentages were not available, and had few post-Han examples to consider.

The cooperation of Edward Sayre as the chemist and Ray Smith as the collector is the widest such study (Smith 1963, 1969, Sayre and Smith 1967). It has revealed patterns in glass composition over 3000 years in Europe, Africa and western Asia.

In the Indian context, papers presented at the Archaeometry of Glass session of the XIV International Congress On Glass (Bhardwaj 1987) contain many analyses and some interpretations of the results. While useful and often citing beads (virtually the only glass product in India for a long time), they lacked a rigorous agenda for interpreting the results. No attempts were made to pinpoint glass beadmaking sources and to compare glass from them. India was treated as though all glass from the vast region should be the same.

As for trade beads in the Americas, an excellent beginning was made by the archaeologist Ian Kenyon and R.G.V. Hancock and his students as the investigating scientists (Hancock, Chafe and Kenyon 1994, Kenyon, Hancock and Aufreiter 1995). Unfortunately, Kenyon's death has put this program on hold.

Two programs have been developed for glass beads in Africa (Davison 1972; Saitowitz, Reid and van der Meer 1996). These are not as useful as they might have been. Both chose to investigate trace elements found in tiny amounts that were not been purposely added. There are no parallel analyses for these and since the two scholars chose different groups of trace elements, their work cannot even be compared to each other. Davison's conclusions were ambiguous. I believe that Saitowitz's has many problems.[5]

To summarize, a program of glass (bead) analysis is optimally based on a carefully planned agenda to answer specific problems. Apples and oranges should not be compared. Specimens should be chosen carefully as to origins and associations.

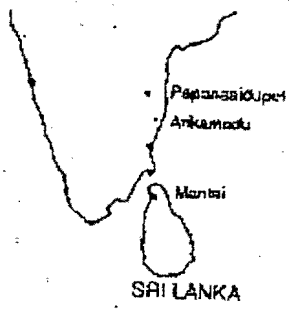
Henderson (1995:67) outlined the types of questions that glass analysis can potentially answer. They include identifying the raw materials and colorants used in glass and finding links between glass composition and bead types, dates, manufacturing sites and other glass products. With this information, much can be learned about glass beads, their origin, trade and cultural affiliations.

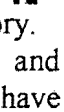
[5] A perceived "cerium depletion" led Saitowitz to conclude that the African beads came from Egypt rather then India or Indo-Pacific beadmakers. However, there is considerable overlap among the beads, the Egyptian beads were not all certainly made in Egypt, the Indian examples were from Arikamedu, while Mantai or Srivijaya were more likely sources, her assumption about alkali sources is misleading, there are alternate explanations for cerium depletion and the beads were not carefully selected; they even include a Venetian green heart.

Analyses of Indo-Pacific Beads

Background

Indo-Pacific beads are small monochrome drawn glass beads, the first seed beads. They were the dominant beads in much of the Old World for 2000 years. They were the most important trade beads, perhaps





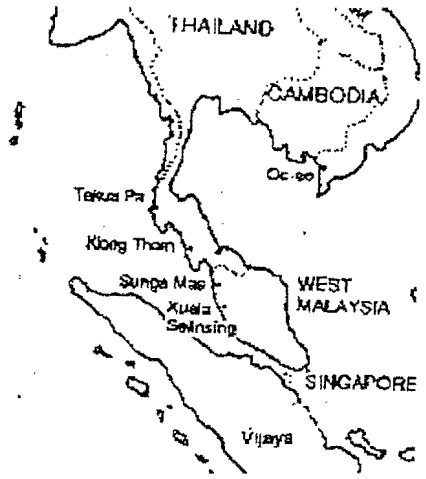
the most important trade item, in history.

Readers of the *Margaretologist* and some of my other works know that I have been researching these beads for twenty years. As this work drew to its conclusion with the Arikamedu final report and a book on beads in the Asian maritime trade, questions about them persisted.

As far as can be determined, these beads were first made at Arikamedu, on the Southeast coast of India. A few miles south of Arikamedu the port of Karaikadu was occupied in the early centuries AD. It also made them, probably in conjunction with Arikamedu.

Around the first century, AD, some Indo-Pacific beadmakers migrated from Arikamedu to three other locations. One was Mantai, in northern Sri Lanka, then allied with South India. The other two were in Funan, the first state in Southeast Asia: Oc-eo, Vietnam and Khlong Thom, Thailand. These were apparently the eastern and western ports of Funan (or close to the ports), and facilitated commerce between India and China.

In the 7th century, Funan was overrun by the Khmers of Cambodia and lost its role in commerce. This was assumed by



Srivijaya, based in Sumatra, with its capital at modern Palembang (anciently probably called Vijaya). Srivijaya controlled much of Java and the Malay Peninsula, thus the waterway (the Malacca Strait) and the overland routes that connected India and China.

Four sites in Srivijaya made Indo-Pacific beads: Vijaya, Kuala Selinsing and Sungai Mas, Malaysia and Takua Pa, Thailand. Kuala Selinsing may never have been a port, shipping its products out from Sungai Mas. In the 10th century, Sungai Mas succeeded Kuala Selinsing as beadmaker. Takua Pa was occupied only in the 9th century, perhaps an attempt by Srivijaya to control the overland routes.

Mantai, Sri Lanka, was abandoned in the 10th century. Srivijaya lost power in the 12th century. All this time, Arikamedu continued to make beads, and became the only beadmaker again around the 12th

century. By the 17th century it, too, was abandoned and the beadmakers moved north to the village they currently occupy, Papanaidupet, Andhra Pradesh.

This is a remarkable story of beadmaking in at least ten sites in six modern countries for more than 2000 years. It has been pieced together by identifying the unique glass wasters produced by the beadmaking method, particularly the tube drawing technique.

Problems and a Program

I had the outlines of the Indo-Pacific bead story, but was missing many of the details. In particular, I wanted to know the source of the glass. Some scholars had suggested that it came from the West as scrap glass, but the published analyses of beads in this region indicated this was not so (Francis 1988/9:4-9). Was it made at one or two Indo-Pacific centers and shipped to the others to work or did each center make its own? In particular, what was the nature of the glass at Arikamedu, the subject of my most intensive study?

Over the years, I collected Indo-Pacific bead samples from importing and beadmaking sites in South and Southeast Asia from the excavators (surface finds for Karaikadu) in hopes of having them analyzed. My chance came when Ron Hancock of the University of Toronto offered to analyze 20 samples by neutron activation with the SLOWPOKE-2 Reactor.

The first decision was choosing samples to analyze. I concentrated on beadmaking sites. I chose the dominant colors of opaque red and dark translucent blue. I had no samples from Oc-eo. The Mantai samples were being analyzed elsewhere and not available. I eliminated Papanaidupet, as its glass is made at Firozabad in northern India or locally with ingredients from Firozabad.[6]

This was seven sites and fourteen beads, leaving six slots. Because we have dated wasters from Arikamedu, I took four samples from there and added an orange bead from Kuala Selinsing and the distinctive green-blue glass from Vijaya. Finally, I chose two beads from Gilimanuk, Bali, a first/second century importing site to see if we could source its beads.

I sent these samples to Ron Hancock, who analyzed them at the SLOWPOKE-2 Reactor Facility. He placed each into a small plastic vial and sent it into the heart of the reactor where it was bombarded by radioactivity for about a minute. The vial was then retrieved and put into a gamma ray detector. Each element emits a characteristic peak along the gamma ray spectrum. The height and strength of the peak indicate the amount of the element present and a computer program interprets these as percentages (or parts per million).

The brief bombardment affected elements with short half-lives. Within a few weeks, the samples were radioactively cool enough to be returned. Had he bombarded the samples longer they would have detected elements with longer half-lives, but would have remained radioactive for a long period and could not be returned. This meant we could not detect certain elements, notably silica and iron. I did not think the amount of silica was crucial to the investigation. The lack of iron in our analyses was the only drawback.

There are also other analyses from some of these sites previously published. Including our analyses, there are now nineteen available for Arikamedu, fourteen for Kuala Selinsing, eleven for Oc-eo and seven for Takua Pa. Those from Karai-

[6] Firozabad has long been the "glass capital" of India, but is unrelated to the Indo-Pacific industry.

kadu, Khlong Thom, Sungai Mas and Vijaya have only been done in this program.

Tables showing all the analyses of Indo-Pacific beads are posted on www.thebeadsite.com. From the home page click on *Galleries*, then *Color Plates for the Margaretologist* then to *Netscape* or *IExplorer Versions* (depending upon your browser) for issue 11(1).

Some earlier analyses have drawbacks. For Oc-eo, soda and potash were reported as soda only. In some or all but one of the early analyses for Kuala Selinsing and Takua Pa only silica, alumina, lime and copper were analyzed chemically and the rest by arc spectrometry.

The Results

Glass from the West?

The question of whether the raw glass for Indo-Pacific beads came from the West and was merely worked in Asia was discussed a decade ago (Francis 1988/9:4-9), reasoning that it was not. The new analyses strengthen that conclusion

For opaque red (and orange) beads, the Indo-Pacific group differs significantly from glass of this color in the West because it lacks lead. Lead aids the dissolving of the copper to make this color, and virtually all red glass in the West has heavy amounts of lead. There are a couple of exceptions, but they are very rare. On the other hand, no Indo-Pacific red glass has any significant lead content.

At Arikamedu, the blue, black and violet glasses have potash as their major alkali, while this was not the case for Western glass in the first millennium. The alumina in glass from Oc-eo, Takua Pa and especially Kuala Selinsing is very high compared to glasses in the West. Moreover, the magnesium content at Vijaya and Kuala Selinsing is extremely low compared to any Western glasses. In sum, the red glass from all these sites and the glasses of other colors from most of them are so different from Western glasses that they cannot be related.

One or Many Glassmaking Centers?

Not only is the glass from the Indo-Pacific beadmaking sites different from Western glass, but it differs among the sites as well. The red glasses are similar, but the other colors have distinct signatures.

The Arikamedu non-red glass stands apart as it has potash as its major alkali. The glass of Kuala Selinsing has very high alumina and very low manganese, separating it from all the others. Oc-eo and to some extent Takua Pa share the high alumina content, but only Vijaya shares the low manganese concentration. Only Vijaya made translucent green-blue glass, which also sets it apart (Mantai made a unique opaque blue-green glass).

There are some similarities. The glass of Karaikadu and Arikamedu are virtually identical, not surprising given their proximity. The glass was either made with the same recipe or at the same place.

The major difference between the glass of Oc-eo and Khlong Thom is that the Khlong Thom blue is colored in the same way as the Arikamedu blue (see below). These two places were politically connected and might have had one glassmaking center. We need more analyses from both places. We have only our two from Khlong Thom and the published Oc-eo analyses need to be supplemented.

The other possible glass group is from Srivijayan sites: Vijaya, Takua Pa and Sungai Mas (but not Kuala Selinsing, which may be earlier). There may have been a single origin for their glass, but we need more analyses to be sure of that.

Glassmaking at Arikamedu

A major surprise to me was what we learned about glassmaking at Arikamedu. The different alkalies for different colors

(soda for red, potash for the others) were already known.

The colorants are also interesting. Copper was used for opaque green and red. Iron was used for translucent green (never made into Indo-Pacific beads), some of the "black" and presumably opaque yellow. Manganese was used for the violet and the rest of the "black."

But what about the second (to the red) most popular color, the dark blue? It is a rich shade, often purplish-blue. It looks like a deep cobalt blue, but no cobalt had been detected. The first analysis of Arikamedu beads by Subramanian (1950) was of this color. He found a high manganese concentration and rightly noted that the violet of manganese is shifted toward the blue end of the spectrum in a potash environment.

However, the SLOWPOKE analyses shows that there is cobalt in small but significant amounts in the blue beads. Being a strong colorant this can account for the blue, especially with the manganese/potash combination. Yet, the cobalt is in such small amounts it cannot have been purposely added. Had it been there would also have been a corresponding arsenic content, since cobalt ores are arsenious. And even if it were, why would the manganese have been added?

The answer must lie in the raw material used, and that has to have been the impure manganese ore with the unlikely name of wad (also called "bog manganese"). Wad often contains a small amount of cobalt. It is available in India, and its source was accessible to Arikamedu. It is found in southern India in the region between the Krishna and Godavari Rivers.

Not only is this region close to Arikamedu, but it is also the area that I have previously identified [1993 6(2):4] as the source for most of the semiprecious stones cut there. The young Pandukal horsemen were most likely responsible for bringing diamonds (for drilling), agate, carnelian and almadine garnet from this area, as well as wad and free copper for the glassmakers of Arikamedu.

Not all wad has cobalt, and the deposits without cobalt would have made violet and black glass. No doubt it was quickly learned which deposits would produce blue glass and which violet/black.

The manganese-potash-cobalt combination for dark blue glass is also evident elsewhere. This includes Gilimanuk, the importing site in Bali, which evidently got its beads from Arikamedu (there were collar beads there too, also from Arikamedu). A dark blue bead from Takua Pa and one from Kuala Selinsing also had manganese-cobalt, but not potash suggesting that wad might have been imported from India by these glassmakers.

The judicious choice of only 20 samples has been revealing. The new analyses confirm Indo-Pacific glass as Asian and the independence of the beadmaking sites, most even making their own glass. The revelations about the Arikamedu dark blue glass and the early import of Arikamedu beads to Bali are also important.

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Table 1 Some elements found in glass.

Al = aluminum	**Mn = manganese**
As = arsenic	**Na = sodium**
B = boron	**P = potassium**
Ba = barium	**Pb = lead**
Ca = calcium	**S = sulfur**
Cl = chlorine	**Sb = antimony**
Co = cobalt	**Si = silicon**
Cu = copper	**Sn = tin**
Fe = iron	**Ti = titanium**
Li = lithium	**V = vanadium**
Mg = magnesium	**Zn = zinc**

TABLE TWO

SLOWPOKE–TORONTO ANALYSES OF INDO–PACIFIC BEADS AND GLASS
(In percentage of element)

	Ca	Cl	Co	Cu	Al	Mg	Mn	Na	Sn	Ti	V	As	K	Sb
01	2.56	0.79	≤0.003	1.24	1.89	≤0.54	0.15	8.72	≤0.09	≤0.01	0.008	≤0.007	4.21	≤0.008
02	3.87	0.78	≤0.001	≤0.03	2.69	1.45	0.09	2.06	≤0.04	0.02	0.003	≤0.002	5.78	≤0.003
03	≤0.62	0.19	0.04	≤0.10	0.90	≤1.41	1.5	≤0.26	≤0.27	≤0.37	0.006	≤0.002	12.4	≤0.003
04	≤0.86	≤0.23	≤0.01	≤0.12	1.40	≤2.99	4.8	≤0.54	≤0.33	≤0.48	≤0.002	≤0.003	14.9	≤0.003
05	1.08	0.68	≤0.002	0.64	5.03	≤0.03	0.02	11.3	≤0.07	0.21	0.007	≤0.008	2.21	≤0.009
06	1.79	0.67	≤0.003	1.45	4.48	≤0.21	0.05	10.3	0.25	0.28	0.007	≤0.007	1.15	≤0.13
07	2.94	0.27	≤0.004	7.01	5.91	≤.22	0.04	10.7	0.34	0.28	0.009	0.02	1.60	≤0.011
08	1.87	0.39	≤0.003	1.68	3.13	≤.50	0.13	11.2	≤0.1	≤0.14	0.005	≤0.008	1.68	≤0.011
09	≤0.29	≤0.03	0.02	≤0.06	.2.28	≤0.34	0.5	0.24	≤0.1	≤0.17	0.004	≤0.01	13.5	≤0.012
10	2.49	1.05	≤0.003	1.03	5.10	≤0.15	0.05	9.44	0.2	0.31	0.005	≤0.005	1.07	≤0.008
11	1.32	0.65	≤0.002	0.45	2.41	≤0.48	0.03	13.2	≤0.07	0.29	0.01	≤0.009	≤0.64	≤0.015
12	3.75	0.58	≤0.003	0.53	4.68	≤.26	0.05	12.9	≤0.09	0.32	0.01	≤0.008	1.35	≤0.011
13	2.30	0.69	≤0.003	0.31	5.50	≤0.08	0.05	9.71	≤0.09	0.32	0.01	≤0.006	1.34	≤0.01
14	2.88	1.05	≤0.003	≤0.07	2.58	≤0.59	0.17	10.7	≤0.09	≤0.14	0.003	≤0.006	3.13	≤0.008
15	2.57	1.14	≤0.002	0.71	5.44	≤0.12	0.05	11.0	≤0.08	≤0.12	0.01	≤0.007	1.37	≤0.008
16	3.72	0.53	0.004	≤0.11	0.81	3.70	1.05	10.7	≤0.2	≤0.27	≤0.002	≤0.004	1.56	≤0.005
17	1.42	0.82	≤0.003	1.33	6.23	1.32	0.06	9.93	0.24	≤0.14	0.005	≤0.007	2.24	≤0.01
18	2.72	0.78	0.03	≤0.13	2.37	≤1.55	1.71	9.56	≤0.29	≤0.40	0.01	≤0.01	≤0.90	≤0.014
19	1.41	0.69	≤0.003	1.53	3.08	≤0.43	0.12	10.8	0.21	0.30	0.006	≤0.006	1.41	≤0.009
20	≤0.71	≤0.08	0.04	≤0.14	1.19	≤1.68	1.46	0.56	≤0.3	≤0.47	0.01	≤0.004	11.8	≤0.004

Sources: 1. Arikamedu red chunk, early. 2. Arikamedu black chunk, early. 3. Arikamedu dark blue chunk, early. 4. Arikamedu black chunk, late. 5. Kuala Selinsing, light blue. 6. Kuala Selinsing, red. 7. Kuala Selinsing, orange. 8. Gilimanuk, red. 9. Gilimanuk, dark blue. 10. Vijaya, red. 11. Vijaya, dark blue. 12. Vijaya, green-blue. 13. Sungai Mas, red. 14. Sungai Mas, dark blue. 15. Takua Pa, red. 16. Takua Pa, dark blue. 17. Khlong Thom, red. 18. Khlong Thom, dark blue. 19. Karaikadu, red. 20. Karaikadu, dark blue.

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