Glass Technology of the Past
Preparing for the Future

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James W Lankton
Honorary Senior Research Associate
Material Culture and Data Science
UCL Institute of Archaeology
London
jamesyuri@gmail.com
Organization of presentation

1. Why do we study glass?
2. How do we study glass?
3. Past scientific studies of early glass in India
4. Current understanding of early Indian glass production and exchange
5. Emerging themes
6. The future of the past: How to get from here to there?
Glass is one of the earliest man-made high technology materials. Glass objects were important in most early societies:

- Marker of prestige and cultural identity
- Often very valuable—combined glass with gold
- Commonly used for protection and worship

Insight into multiple aspects of early societies:

- Production: Technology, methods and means, *chaine operatoire*
  - Primary production (raw glass) and secondary production (objects)
  - Separate and distinct industries: technological requirements, workers, organization of production

- Exchange and trade
  - Both raw glass and finished objects
  - Critical aspect of development of early societies

- Consumption of glass articles within societies
  - Social structures and differentiation
  - Ideology and religious systems

Glass has its own language that when unlocked can lead to many insights into the ways people lived in the past.
2.1 How do we study glass? Four approaches

- **Typology:** Physical description and measurement
- **Technology:** How objects were made, provenance of objects, beads drawn vs wound
- **Archaeology and text:** Ancient descriptions, archaeological context including dating and associated materials
- **Scientific analysis:** Where the glass itself was made, ancient technological traditions, geological provenance

Method of study must respond to the archaeological questions

Most useful to include all four approaches
2.2 Chemical compositional analysis: What do we measure?

Silica source to provide ‘backbone’ for the glass
- Sand
- Quartz pebbles or crushed siliceous stones

Flux to lower melting temperature
- Alkaline mineral deposit (m) MgO<1.5 %
- Plant-ash alkali (v) MgO >1.5 %
- Lead

Coloring or opacifying agents
- Oxides
- Metallic salts

Si, Al, Fe, Ti, Ca, K, Mg, Zr, U, REE…
Na, K, Ca, Mg, Cl, P, trace elements Rb, Sr
Transition elements, Cu, Co, Sn, Pb, trace elements

• Chemical composition reflects the glassmaking recipe and the underlying geology of the source area
• Trace elements critical for matching compositions to create a ‘fingerprint’ for the glass, but also affected by crucibles, tools
• Outer 100 microns of glass affected by weathering and will give misleading results
2.3 How do we study glass: Scientific analysis

Chemical compositional analysis for major (>1.0 wt%000), minor (0.1 to 1.0 wt%) and trace (<0.1 wt% or 1000 parts per million (ppm))

- Techniques including imaging: Scanning electron microscopy-based with varying qualities of X-ray detectors
  - SEM-EDS (scanning electron microscopy with energy-dispersive spectrometry) vs EPMA (electron probe micro-analysis) both excellent but only for major and minor elements

- Techniques including mass spectrometry: Liquid (dissolve sample) or solid (laser) sampling
  - More than 50 elements determined with precision and accuracy in 10% range for laser sampling, better for liquid sampling
  - LA-ICP-MS (laser ablation-inductively coupled plasma-mass spectrometry) virtually non-destructive, yet full coverage for major, minor and trace elements

- Trace elements essential for provenance studies since glasses from distant areas may be very similar in terms of major and minor elements: eg North India vs South India or India vs ‘Roman’ glass
2.4 Analytical techniques: LA-ICP-MS in Orleans, France

- Major, minor and up to 50 trace elements
- 5 to 20% accuracy and precision
- Rapid throughput: 40-50 samples per day
- No sample preparation
- Invisible sampling but below surface
- Excellent for polychrome glasses
2.5 Analytical techniques: LA-ICP-MS

- **Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry**
  - Introduced for glass study over ten years ago by Bernard Gratuze
  - Multi-element coverage- 40 or more elements analysed, including major (>1%), minor (0.1-1%) and trace (0.1% to 0.0001% or less)
  - Small amount of glass removed by laser- leaves tubular hole 100 microns (0.1 mm) or less in diameter, approximately 200 microns deep
  - No sample prep, invisible to naked eye, virtually non-destructive

**Least destructive of quantitative techniques!**

After testing

Laser holes with glass scatter

Glass wiped clean
Isotope ratio analysis for strontium (Sr), neodymium (Nd) and lead (Pb)

- Ratio of radiogenic to stable isotope for one of the components of the glass
  - Index of geological age of materials used to make the glass
  - Strontium generally reflects lime (CaO) provenance
  - Neodymium reflects silica (SiO2) provenance
  - Lead isotopes also useful

Isotope ratios can help to answer questions not answered by chemical composition alone
3.1 Past scientific studies

- 1920s and 1930s: M Sanaullah and Hamid Harappan faience as well as glass from Taxila, Nalanda, Agra, Kurukshetra and others
- Analyses of glass from individual sites
  - B B Lal 1952: Ahichhatra
  - P Roy and Y P Varshney 1953: Kopia
- Actual data from these studies difficult to use because
  - Qualitative
  - Missing elements

Two milestones in research on early glass in India

- M G Dikshit 1969: History of Indian Glass
  - Collected papers in two sections: ‘Indian’ (including some Central Asian) and ‘Non-Indian’ (Indonesia, China, Japan)
4.1 Current understanding of early Indian glass

Changes in the conceptualization of early India

• More nuanced definition of ‘What is India?’
  • Increased understanding of relationships between South and Southeast Asia
  • Ian Glover and Julian Henderson 1995: Early glass in South and Southeast Asia and China
  • Sheldon Pollock: Similarities between India and Southeast Asia in terms of development of cosmopolitan culture
  • ‘…in the first millennium, it makes hardly more sense to distinguish between South and Southeast Asia than between north India and south India.’ (Pollock 2006)
  • Can we find a similar pattern in the development and transfer of certain technologies?

The study of early Indian glass not confined to India
4.2 Current understanding of early Indian glass

Evolving assumptions about early glass in general

• Primary glass production was usually a transferred technology-independent invention must be proved rather than assumed
  • Good example: Late Bronze Age transfer of glass technology from Mesopotamia to Egypt only after Egyptian military incursions into Syria and probable relocation of Syrian glassworkers to Egypt
  • Known examples of ‘independent’ invention are special cases where glass was known for an extended period of time, and then fabricated in new ways
    • China ca 5c BCE: Production of lead-barium glass after several centuries of glass beads imported from western Asia
    • Nigeria 10-12\textsuperscript{th}c CE: Production of HLHA (high lime-high alumina) glass after almost 1000 years of exposure to imported glass beads
• Glass production not a logical consequence of other vitreous technologies like faience production
  • Egypt: 2000 years of faience but no native glass industry
  • China: Imported then locally produced faience, but no locally produced glass until glass itself was imported
Two archaeological questions for this presentation

• What chemical compositional groups are present?
• Can we identify any emerging themes in Indian glass study?

Start with database of 569 glass samples, almost all beads

• Most of the analyses by LA-ICP-MS and include ca 50 major, minor and trace elements
  • Analyses by Laure Dussubieux, Bernard Gratuze, James Lankton, Robert Brill

• Samples from 7 states, although 90% of samples from 3 states: Tamil Nadu (54%), Uttar Pradesh (24%) and Maharashtra (14%). Large parts of India with no data at all

• Almost all of the samples were found at particular archaeological sites, but very few have a clear context within the site, and even fewer can be assigned specific dates based on modern dating techniques
4.4 Current understanding of early Indian glass

Results based on LA-ICP-MS analyses

13 chemical compositional types identified

• Distinguished by major alkali: soda (Na2O), potash (K2O), or mixed Na2O and K2O

• Source of alkali: mineral (magnesia (MgO) <1.5 wt%, or plant ash (MgO >1.5%)

  • These categories work well for Middle Eastern glass, but less well for Asian glass where sources of alkali could have been more varied - eg leached plant ash may look like mineral soda or potash

• Relative and absolute levels of lime (CaO) and alumina (Al2O3)

• Trace elements: Importance of individual elements varies case by case, but in general uranium (U), zirconium (Zr), barium (Ba), strontium (Sr), rubidium (Rb), titanium (Ti), thorium (Th), cesium (Cs) always useful. REE often useful

• 7 of the chemical types account for over 80% of samples

• Most of the compositional groups are compatible with a South Asian origin while at least 3 groups more likely represent imported glass
4.5 Current understanding of early Indian glass

1. Mineral soda glass with high alumina (47% of samples)

   Identified by Brill as an Indian-made compositional type
   - Suspect ‘mineral’ source of flux because of low magnesia (MgO)
   - Alumina (Al2O3) > 3.4-4 wt% and sometimes > 12 wt%
   - Lime (CaO) typically below 4.5-5 wt% as suggested by Brill
   - Wide distribution ‘from Bali to Mali’

   Four subgroups based on trace element analysis: U, Ba, Sr, Zr and Cs
   - Identified by Dussubieux as m-Na-Al 1 to 4
   - Subgroups important because they correlate with different archaeological meanings
     - These subgroups could not be identified without trace elements. Provides one of best illustrations of the importance of trace element analysis

   Two subgroups (1 and 3) found in pre-9th c. CE samples
   - m-Na-Al 1: high Ba and low U (South India and Sri Lanka)
   - m-Na-Al 3: low Ba and high U (North India)
4.6 Current understanding of early Indian glass

2. Potash glass with moderate lime and alumina (m-K-Ca-Al)

- 16% of total samples
  - Drawn beads, beadmaking waste
  - Colours cobalt blue (69%), opaque yellow, black, violet, green, greenish blue
  - Alumina and lime both generally between 2 and 4 wt%

- Most of samples from Arikamedu, but also Kausambi and Kopia
  - Up to 40% of the Arikamedu samples in Pondicherry Museum may be potash glass
  - Arikamedu potash glass has Sr isotope ratio of ca 0.72-0.74

- The ‘Indian’ type of m-K-Ca-Al does not appear to predate 1st c.
- Possible ingredients for primary production include saltpetre (KNO3), known to have been produced in northern India from at least ca 1000 CE
- Likely that potash glass of various types produced at a number of sites and traded widely
3. Mineral soda-lime glass moderate lime and alumina (m-Na-Ca-Al)

9% of total samples distributed from Tamil Nadu to Uttar Pradesh

- Lime (2-6 wt%) and alumina (3-8 wt%) highly variable
  - Based on major and minor elements alone may be difficult to distinguish from Eastern Mediterranean natron glass and from North Indian m-Na-Al type 3

- Drawn beads, zone beads, fragments; colours include Co blue (34%)

- Very similar mineral soda glass probably produced in southern Thailand ca 2nd to 6th c. CE at site of Khuan Lukpat
  - Evidence includes large blocks (several kg) of partially formed glass, as well as fragments and objects made from this glass
  - Similar glass at several Thai-Malay Peninsular sites, including cobalt-blue
  - Sr isotope analysis consistent with coastal production, not North India

Was the m-Na-Ca-Al glass found in India made in Southeast Asia?
RbO by SrO for m-Na-Al 3 glass from Uttar Pradesh (UP) and Tamil Nadu (TN) vs m-Na-Ca-Al glass from UP, TN, Ban Kluay Nok (BKN) and Khuan Lukpat (KLP). KLP KTPR m-Na-Ca-Al glass is most likely primary glass made at KLP.
4 and 5. Two glasses where either two ingredients or two glass types seem to have been mixed together (2% of samples)

m-mix-Ca-Al: Mineral alkali glass made by mixing potash (m-K-Ca-Al) glass with soda glass (m-Na-Ca-Al)

- Very similar to powder glass beads made in Korea by mixing North Indian soda-alumina glass with potash glass
- Ratio of K2O to total alkali ca 60% by weight
- Mostly opaque green drawn beads
- All samples found in Tamil Nadu, most from Arikamedu
- One production centre?
- Likely production area would be Arikamedu, where both m-Na-Ca-Al and m-K-CA-Al glass were found
- Why glassworkers did this is not known, but similar situation in eastern Java in 5th-6th c.
Soda glass with high alumina, lime and magnesia (v-mix-Ca-Al)

• 11% of samples, not well understood
• Mainly found in Tamil Nadu (Arikamedu, Karur) and Jharkhand (Bihar-Dhalbhum)
• Drawn beads, glass fragments
• Opaque red (70%), black (25%)
• Composition looks like a ‘standard’ high-alumina mineral soda glass to which varying amounts of a substance high in lime, potassia, magnesia and phosphate have been added, more for black than for red beads
  • Additive could be plant ash or possibly some combination of minerals
  • Not clear why this might have been done, but somewhat parallel situation in later Roman opaque red glass
  • Not all soda-alumina red and black glasses follow this pattern

Indian technology adapted into Roman glassworking?
Natron glass: mineral soda-lime glass with low alumina, potassia, U

- 2% of total samples
  - Wound beads, gold-glass beads, drawn beads, fragments, bangles
  - Colours cobalt blue (50%), gold-glass (17%), colourless, opaque red
  - Lime 3-11 wt%, alumina 1.4-3.8 wt%, potassia <2.5 wt%, uranium <2 ppm
  - Trace elements, particularly U, required to distinguish

- Samples from Tamil Nadu (Arikamedu, Alagankulam), Uttar Pradesh (Kopia), Maharashtra (Nevasa) but overall number quite small (12 total)

- Not very powerful support for the import of Roman glass to India mentioned in *Periplus of the Erythraean Sea*, a 1st c. CE mariner’s manual. Why?
  - Looking in the wrong places? Glass from Pattanam excavations will be important in this regard

- More Roman glass samples in Southeast Asia and even Korea than in India—was Roman glass mainly re-exported from India to SE Asia?

So far, Mediterranean natron glass in India is the clear winner for most ink spilt over the least actual evidence
Emerging themes in the study of Indian glass

• Regionalization of glass production
• Exporters and importers
• Targeted exchange: Early business plan?
5.2 Emerging themes: Regionalization

Regionalization of glass production

- Most of data for north vs south but west and east probably also important
- Supports Pollock’s notion of different culture in North and South India
- May have overlap of glass-making technology, but compositional types very little overlap suggesting limited exchange of glass between north and south

<table>
<thead>
<tr>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early urbanization and early glass production</td>
<td>Settlements such as Arikamedu by end of 3c BCE but urban character uncertain</td>
</tr>
<tr>
<td>Dates uncertain, but glass production certainly by 5c BCE and most likely earlier</td>
<td>Glass production likely by end of 2c BCE but not before, eg Arikamedu</td>
</tr>
<tr>
<td>Technology based on river sand and reh</td>
<td>Northern technology but local raw materials?</td>
</tr>
<tr>
<td>Uttar Pradesh: 67% of samples are m-Na-Al 3 vs 0% m-Na-Al 1</td>
<td>Potash glass: Parallel industries vs separation in time or place?</td>
</tr>
<tr>
<td>Wound beads, zone beads, tabular pierced beads, a few mosaic beads</td>
<td>Tamil Nadu: 29% of samples are m-Na-Al 1 soda-alumina glass vs 2% m-Na-Al 3</td>
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<td></td>
<td>Small drawn ‘Indo-Pacific’ beads</td>
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</tbody>
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5.3 Technology transfer from north to south

- **m-Na-Ca-Al 3**
  - 800-500 BCE (?)  
  - Primary production

- **m-Na-Ca-Al 1**
  - 300-200 BCE (?)  
  - Primary production

- **m-Na-Ca-Al 1**
  - 200 BCE-200 CE
  - Primary production

- **???**
  - Secondary production
  - Ban Don Ta Phet

- **???**
  - Primary production

Map adapted from Singh 2008
India mainly a glass exporter

Probable primary and secondary glass production both North and South India

- Most of studied beads were compatible with local or regional production
- Marked contrast with Southeast Asia and Northeast Asia, where much of glass is imported, even if beads locally made
  - Eg Khuan Lukpat (Khlong Thom): Millions of beads, but glass compositional types seem identical to those of South India and Sri Lanka
  - Possible role for trade in glass ingots- some evidence for ingot fragments, with chemical composition similar to South India, at Khuan Lukpat

Could be related to economies of production, where South India had readily available resources for primary glass production, including technical expertise

- Possible exception: Cobalt-blue m-Na-Ca-Al glass
- Probable primary production in peninsular Thailand
- Why was this glass not made in India as well?
  - Maybe it was?
  - Shortage of cobalt?
- Does this make sense if we think that Co-blue potash glass made at Arikamedu?
5.5 Primary glass from South India and Peninsular Thailand

Appur, Tamil Nadu m-Na-Al 1
- partially fused glass
- ceramic
- glassy phase with unreacted fraction

Khuan Lukpat 2-6 c CE m-Na-Ca-Al
- galle layer (chloride melt)
- good glass
- partially reacted ingredients
Targeted exchange

• Relatively little known about methods of glass exchange in early period
  • Likely to have been private rather than governmental?
  • Financed or controlled by guilds?

• Compositional analysis shows uneven distribution of exchanged materials
  • Could be interpreted in terms of ‘targeted exchange’
5.8 Targeted exchange: Arikamedu to Phu Khao Thong

Arikamedu to Phu Khao Thong

• Evidence that Arikamedu was major producer of beads, but very little glass with Arikamedu compositional type found in SE Asia
• Exception is Phu Khao Thong, where glass matches Arikamedu production very closely, including m-mix-Ca-Al and v-mix-Ca-Al
  • Why only there? Probably not chronology, since other sites overlap with Arikamedu as well
• Explain in terms of targeted exchange, possibly controlled by guild
• Transfer of glass technology could have had a role in the development of the site

Relatively large amount of Roman glass, including mosaic vessels, found at PKT as well—more than at Arikamedu itself
5.9 Targeted exchange: Arikamedu to Phu Khao Thong

- **500 BCE - 200 BCE (?):** m-mix-Ca-Al, v-mix-Ca-Al
- **300 BCE - 200 CE:**
  - 300 BCE - 200 BCE (?): Anuradhapura, Muziris
  - 200 BCE - 200 CE: Arikamedu
- **800-500 BCE (?):**
  - 800-500 BCE: Bharukachcha, Sopato, Pratisthana
  - 200 BCE - 200 CE: Ban Don Ta Phet, Khao Sam Kao, Trang, Khuan Lukpad

Map adapted from Singh 2008.
5.10 Targeted exchange: Arikamedu potash glass

Arikamedu soda glass in SE Asia mainly at PKT, but potash glass different picture

• Small cobalt-blue drawn ‘Indo-Pacific’ beads made from potash glass with Arikamedu composition found at many sites in northern Vietnam, NE Asia
• Dates generally late 1c BCE to 4c- compatible with producton at Arikamedu

![Graph showing correlation between CoO and V2O5 for m-K-Ca-Al glass samples from various sources.](image)

• Early type in Thailand high in As and sometimes Ni
• Later type in southern China, Korea, Japan
• This composition very similar to Arikamedu samples
• Was this glass made at Arikamedu? China?

Correlation between CoO and V2O5 for m-K-Ca-Al glass samples from various sources.
5.11 Targeted exchange from Arikamedu to Northeast Asia

- 800-500 BCE (?)
- 400-200 BCE
- 300-200 BCE
- 200 BCE-200 CE

Map adapted from Singh 2008.
Implications of targeted exchange

May suggest vertical integration of supply chain

• Who controlled the exchange?
  • In case of PKT, control from production centre more likely (?)
  • For Arikamedu potash glass to Northeast Asia, interaction between producers and consumers, perhaps with client feedback and specific production for particular markets
    • Closer contact over period of time (?)
How to get from here to there?

Physical development

- Analytical facilities for chemical analysis, including at a minimum LA-ICP-MS and some type of electron image-based spectrometry, whether SEM-EDS (scanning electron microscopy with energy dispersive spectrometry) or EPMA (electron probe microanalysis)
  - Analytical technique tailored to archaeological questions
  - IMHO: Analysis without trace elements is a wasted opportunity
  - Trace elements alone may not be sufficient
- Less immediate, although probably no less important: isotope ratio analysis for such elements as strontium, neodymium and lead
  - Multi-collector ICP-MS (newer technique) vs TIMS
Human resource development

• Dedicated, well-trained technical personnel to oversee, calibrate and repair the above equipment
• Archaeologists familiar with both the archaeological questions and the characteristics of ancient glass
  • Also willing and able to spend the time necessary to learn the principles and pitfalls of new analytical techniques
  • Giving the glass samples to a technician seldom leads to good results

Critical issues of sampling

• Access to glass samples from well-controlled excavations with special attention to dating
  • With such virtually non-destructive techniques as LA-ICP-MS now available, there seems little reason why even glasses destined for eventual display could not be analysed
• One of the biggest obstacles is permission for export, even temporary, of archaeological samples for analysis elsewhere
  • Availability of similar analytical capability within India may be the logical next step
Recapitulation

1. Why do we study glass?
2. How do we study glass?
3. Past scientific studies of early glass in India
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Final thoughts: Where is ‘there’?

• Clear definition of archaeological questions, preferably from planning and inception through excavation
  • International collaboration essential to achieve highest quality results, regardless of where the actual analyses are done
• Glass in ancient world was material *par excellence* in crossing borders and linking cultures
• Glass study today must follow the same pathways
Glass research and ‘The future of the past’

James W Lankton
Honorary Senior Research Associate
Material Culture and Data Science
UCL Institute of Archaeology
London
jamesyuri@gmail.com