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RESEARCH

Glass from Manthai, Sri Lanka: Insights into the supply of glass for the Silk Roads

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Abstract

Manthai served as a port emporium on the Maritime Silk Roads and an intermediary between the Near and Far Eastern realms for over 1000 years. The 1980–1984 excavations conducted by the late Professor John Carswell yielded material goods supporting the importance of Manthai within this extensive trade network. These included glass, some thought to have been produced locally and some believed to be imported from the Islamic world. To better understand the role of Manthai in provisioning glasses for the Silk Roads, 21 8th -13th century AD samples were analysed by LA-ICP-MS for major, minor and trace elements. Results have provided evidence for varied compositions within the Manthai glass samples. There is a m-Na-Al 1 subgroup, to which a sample of raw crucible glass, other raw glass samples and a bangle fragment belong. Samples made using plant ash glass exhibit greater compositional variability, including two subgroups linked to the site of Samarra, some broadly 'Mesopotamian' glasses and two samples likely produced in Central Asia. The results have demonstrated that finished objects were imported from the Islamic World and that glass, possibly produced in the region around Manthai, was used in secondary glass working to supply the Maritime Silk Road. This adds to the evidence for the multi-faceted activities conducted at Manthai including the production and/or shipment of glasses through Manthai, for the Maritime Silk Roads. We have contributed to the overall evidence for glasses travelling along the maritime and terrestrial Eurasian Silk Roads and helped to define interactions across them.

Keywords Glass composition · Trace element analysis · Sri Lanka · Silk Roads glass movement · LA-ICP-MS

Introduction

The archaeological site of Manthai (8°59′22″N 79°59′53″E) is in what is now known as the Mannar District of north-west Sri Lanka. It is known to have served as a port emporium for Indian Ocean trade and a node of contact between the Middle and Far Eastern worlds (Carswell 1990). In this role the site supported communication, trade and movement of ideas between the Islamic and Chinese worlds via the Maritime Silk Roads.

One of the major factors contributing to the development of Manthai's prominence is its strategic location. The site is located close to Adam's Bridge across the Gulf of Mannar, between Sri Lanka and India (see Fig. 1). This natural geography causes the passage of large sea-faring vessels to be blocked and creates a demand for a proximal port settlement here (Carswell 1990). Wider regional geography means the resulting settlement will have maritime trade contact with both the Islamic World to the west and China to the east. Manthai has also been linked to the historic regional capital of Anuradhapura around 80km to the south (Carswell 1990).

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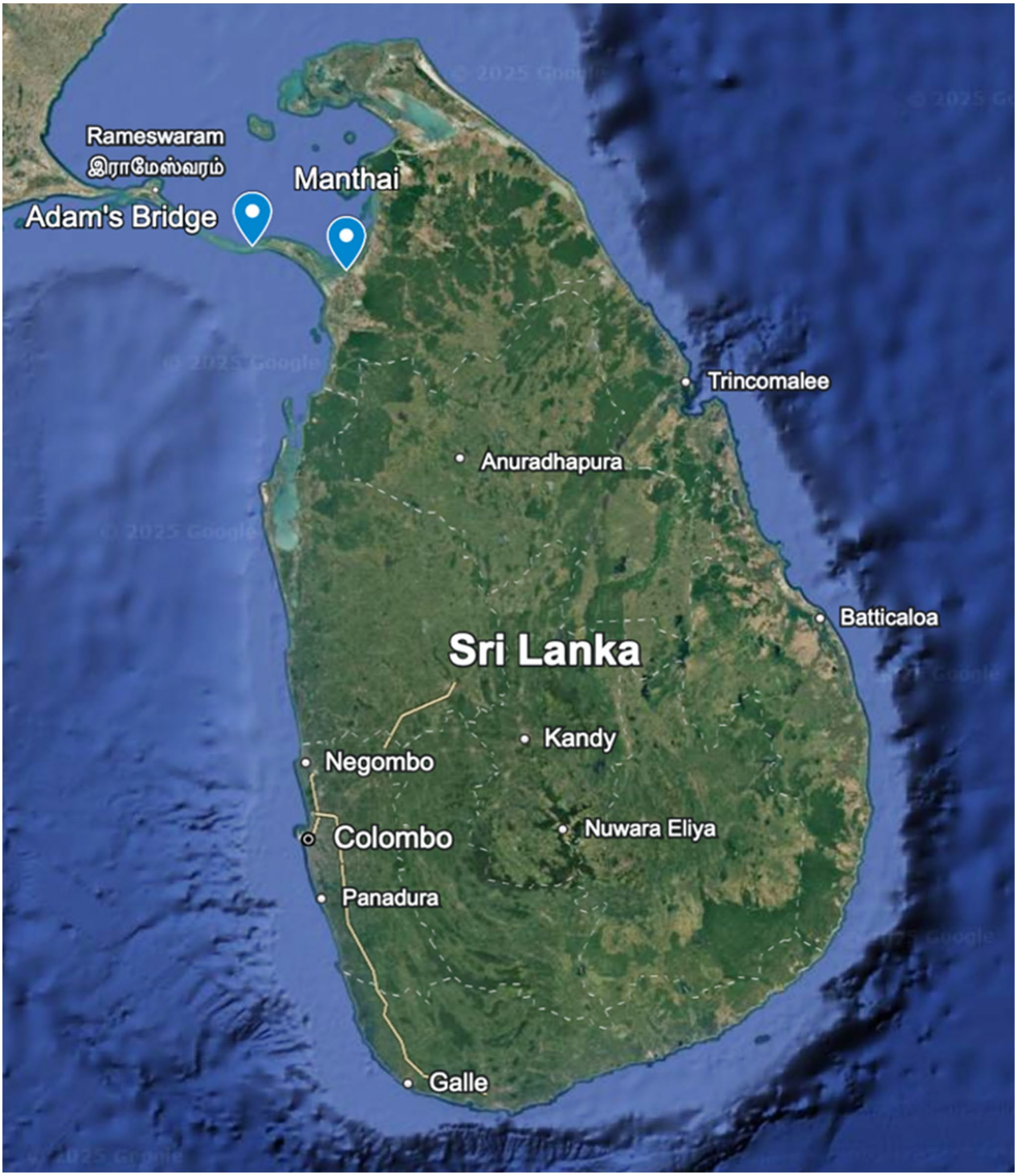


Fig. 1 Map showing the location of Manthai in Sri Lanka and the proximity of the site to Adam's Bridge – a contributing factor to the importance of the site in trade

The site has been subjected to multiple seasons of excavation since it was initially rediscovered by Portuguese forces during their 16th century AD occupation of Sri Lanka (Shinde 1987). Excavations of various limited scales were carried out at the site beginning in 1887 with the first person to recognize the cultural importance of Manthai, A.M. Hocart, conducting excavations in 1926–28 (Shinde 1987). The most significant excavations of the site were conducted by John Carswell beginning in 1980 prompted by him questioning why large quantities of Chinese celadon pottery came to be found in Syria given the difficulties of transporting celadon over land (Carswell 1989). His work unearthed evidence of occupation at Manthai since the 2nd millennium BC and derived a chronology for the occupation sequence of the site (Bohingamuwa 2017). Further excavations were carried out at Manthai in 2009 and 2010 by the Sealinks project based at Oxford University. However, these were more limited in area compared to John Carswell's excavations (Bohingamuwa 2017).

Manthai in the early historic period

All the material discussed in this paper dates to the period Carswell refers to as the Middle Historic (8th to 13th centuries AD), the last phase of occupation prior to the settlement's destruction. At this time Manthai was at its peak, both in terms of size (c. 30 hectares in area) and importance as port emporium and intermediary site between the Near and Far Eastern realms. The settlement was shaped like a horseshoe and featured a double moat and double rampart walls (de Vos 2018). The low mud structure of the walls and fact that the nearby water tank post-dates the moats by at least a century (the moats have been dated to the 2nd −4th centuries AD and the tank to the 5th century AD) suggest these were for water storage as opposed to settlement defence (Shinde 1987). The survival of the site has been attributed to its location in an arid climatic zone, protected from erosion by monsoon rains. This would have additionally rendered the soil unsuitable for agriculture, leading to a solely trade-based focus of the site and the importance of its link to Anuradhapura for its continued survival (Shinde 1987).

The evidence for the involvement of Manthai in long-distance trade is extensive as seen in the material culture recovered from 7th to 11th century strata. These include ceramics such as Chinese celadon, Islamic lustre wares and Rouletted and Red and Black wares (Shinde 1987). The glasses excavated from this period paint a similar picture of many and varied connections – 97% of Manthai glasses were recovered from 8th −13th century AD contexts and reported to originate from the Islamic world. The term 'Islamic glass' will be used here for glasses determined to have been fused as raw materials in the Islamic world (Carboni 2013). The majority of samples studied in this paper derive from 9th −10th century contexts based on stratigraphy and associated ceramics (Pers. Comm. Professor John Carswell). The dates of the Manthai strata are supported by later radiocarbon dating conducted by Kingwell-Banham et al. (2018). Some of the glass shows an interesting connection to Late Sasanian glass working traditions as well as glasses suggested to have derived from Siraf which are known to have been highly desired in the Chinese market (Pradines 2016). It was further suggested by Pradines (2016) that these glasses could have been imported in the form of cullet to be used in local or regional bead production as Manthai is well attested as a site active in the Indian Ocean glass bead trade, especially Indo-Pacific beads. It was for this reason that non-bead glass forms are the focus of this study, with mostly samples of raw glass being analysed.

Imported materials add detail to our knowledge of Manthai's role in long-distance trade showing it as a centre of export trade and transshipment. The role of the site in the period referred to by Carswell as the Early Historic (3rd to 8th centuries) as a Chinese trade intermediary appears to shift over the period to be more focused on exchange with the Islamic Arabian Gulf (De Saxcé 2016). Excavated materials reflect the place of Manthai in several trade networks, one linking the site to the Islamic World and another using glass which was possibly made in the local region. Therefore, we already know that the site was involved in some localized networks for provision of raw materials and goods distribution, local and inter-regional land routes and maritime long-distance trade (De Saxcé 2016).

For this study Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) was used to analyse the vitreous samples from Manthai because it is known to be the most sensitive technique for determining the elemental concentrations at the ppm and ppb level. This analysis was carried out to determine the raw materials used to make the glasses, to identify the colorants used in them, and to attempt to provenance the glasses. The overall aim of the project was to suggest how the glasses analysed from Manthai could provide evidence for trade and interaction along the Maritime Silk Road, potentially between Western Asia, Southwestern Asia and East Asia.

Materials and methods

Materials

All 21 samples discussed here were provided to Professor Julian Henderson (JH) by the late Professor John Carswell from his 1980–1984 excavations. They were selected as representative of the excavated glasses in terms of colour and artefact type so as to investigate the possible evidence for glass working at Manthai. They were analysed using LA-ICP-MS following Electron Probe Microanalysis (EPMA). EPMA results produced by JH formed part of an unpublished MRes thesis by Ms Samantha Dobson and showed the presence of at least two major compositional groups. These groups were characterized by differences in soda source and suggested geographically diverse glass making origins. For this reason LA-ICP-MS was performed on a selection of 21 samples, the results of which are the focus of this article.

A list of the samples selected for LA-ICP-MS is given in Table 1. Nine of the samples are raw glass, including one sample taken from a crucible (MNT19) and one from a glass layer attached to another raw glass in a contrasting colour (MNT29). The remaining samples were chosen to represent a range of finished products such as bowls, flasks and bottles, a bangle and other vitreous products such as faience and glaze. All samples come from glasses attributed dates between the 8th to 13th centuries AD (Carboni 2013); the majority analysed are 9th −10th century in date (Pers. Comm Professor John Carswell). Figure 2 shows photos of MNT 5, 7, 14, 16, 20, 23, 25, 26, 27 and 30 to represent the colours and forms of glasses sampled for this study.

Table 1 The glass samples from Manthai (PA=plant ash; m=mineral; v=vegetal)

Sample No.	Compositional Group	Colour	Description
MNT5	PA2	Pale Green	Raw Glass
MNT6	m-Na-Al 1	Opaque Red	Disc
MNT7	v-Na-Al	Pale Green	Vessel Base
MNT9	m-Na-Al 1	Intense Dark Brown	Raw Glass
MNT14	PA2	Cobalt Blue	Raw Glass
MNT15	m-Na-Al 1	Blue	Undiagnostic
MNT16	Low Mg	Dark Green ‘Black’	Raw Glass
MNT17	PA2	Aqua	Raw Glass
MNT18	PA2	Green Glaze	Faience
MNT19	m-Na-Al 1	Turquoise	Raw Crucible Glass
MNT20	PA2	Opaque Red	Raw Glass
MNT21	PA1	Colourless	Tesserae
MNT22	m-Na-Al 1	Dark Green ‘Black’	Raw Glass
MNT23	PA2	Opaque Red	Raw Glass
MNT24	PA1	Pale Green	Flask
MNT25	PA1	Colourless	Bowl Rim
MNT26	MNT26	Cobalt Blue	Bottle Neck
MNT27	v-Na-Al	Emerald Green	Bowl Rim
MNT28	Low Mg	Pale Olive Green	Flask
MNT29	m-Na-Al 1	Opaque White	Layer on Raw Glass
MNT30	m-Na-Al 1	Dark Green ‘Black’	Bangle Fragment

Methods

Glass samples of approximately 2–3 mm in size were cut from the fragments listed in Table 1 and embedded in epoxy resin. The resin blocks were ground using silicon carbide (SiC) papers of various grits (320, 800, 2000, 4000) and further polished with diamond pastes of 6–3 µm and 1 µm. This resulted in flat, clean surfaces suitable for EPMA and LA-ICP-MS analysis. The prepared blocks were additionally carbon coated to avoid any charging phenomena during the EPMA process. A full range of trace elements were detected using an LA-ICP-MS instrument with a NewWave UP193FX excimer (193 nm) laser system coupled to an Agilent 7500 series ICP-MS. The analyses were performed at the British Geological Survey, Keyworth by Dr S. Chenery and Dr A. Oikonomou. The protocol followed during these measurements had a typical fluence of 2.8 J cm-2, the laser ablation craters were set at a diameter of 70 µm, and the laser being fired for 45 s at 10 Hz.

The acquired data was collected in a time resolved analysis mode, with a gas blank being measured before a series of ablations on glass samples, the calibration standard (NIST SRM 610) and quality control standard (NIST SRM 612 – see Tables 2 (above) and 2 of Online Resource) were completed. Three measurements on each sample were made and the mean value was calculated. Calibration standards bracketed the samples and quality control (QC) over a period of 1 h or less with calibration calculations being performed in iIolite version 2 and any further calculations in Excel spreadsheets.

Results

The full LA-ICP-MS results are given in Table 1 of Online Resources and the means and standard deviations for selected major and minor oxides and trace elements can be seen in Table 3. Based on these major, minor and trace elements two major compositional groups have been identified based on soda source – one mineral (Manthai m-Na-Al) and the other plant ash. Of the glasses made using plant ashes as a soda source two sub-groups (PA 1 and 2 – ‘PA’ referring to the use of plant ash in the manufacture of Manthai glasses) have been identified based on alumina contents as well as concentrations of a range of impurities. The remaining plant ash glass samples have been sub-divided into three further compositional variations consisting of 2, 2 and 1 samples. They are too few to constitute sub-groups (see Table 3).

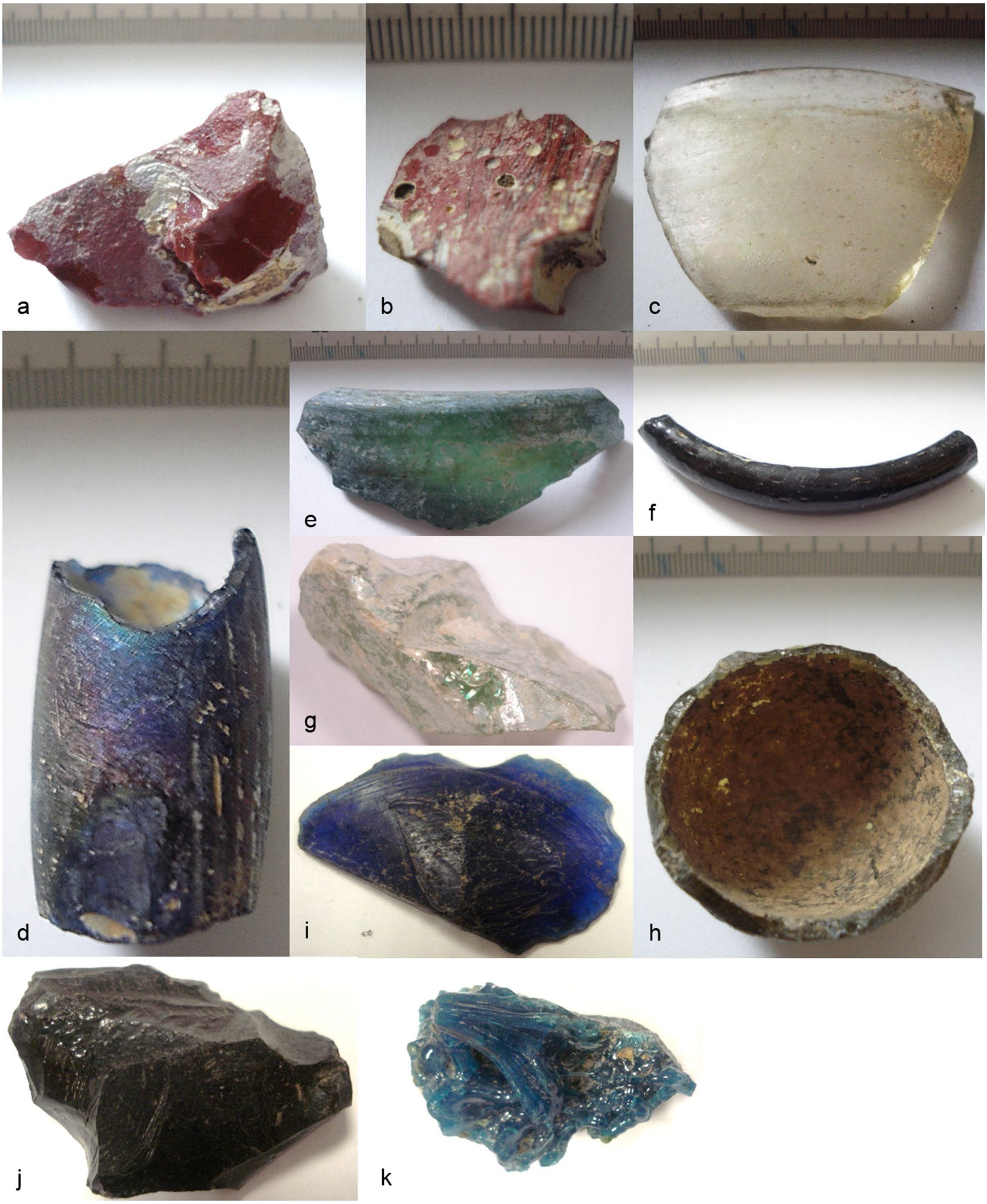


Fig. 2 (**a**) MNT20, (**b**) MNT23, (**c**) MNT25, (**d**) MNT26, (**e**) MNT27, (**f**) MNT30, (**g**) MNT5, (**h**) MNT7, (**i**) MNT14, (**j**) MNT16, (**k**) MNT19. (Photos: J. Henderson)

Table 2 Quality control of the LA-ICP-MS results for NIST 612 standard reference material

NIST 612	Li	B	Na	Mg	Al	P	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni	
Measured Value	40.2	35.3	101220.0	58.3	10740.0	98.7	58.8	85350.0	403	38.7	35.9	38.1	48.2	34.4	39.6	
Sd	1.0	1.4	665.7	1.9	35.2	11.4	4.5	345.0	2.5	0.4	0.6	0.5	0.7	0.3	0.7	
RSD	2.5	3.9	0.7	3.2	0.3	11.6	7.6	0.4	6.1	1.1	1.6	1.3	1.4	1.0	1.8	
Expected Value	40.2	34.3	101632.0	68.0	10743.0	46.6	62.3	85049.0	44.0	38.8	36.4	38.7	51.0	35.5	38.8	
%Error	0.0	2.8	-0.4	-14.3	0.0	111.7	-5.7	0.4	-8.4	-0.3	-1.4	-1.5	-5.5	-3.0	2.0	
NIST 612	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Cs	Ba	La	Ce	
Measured Value	38.0	37.7	34.3	31.8	79.0	38.9	38.5	38.4	36.5	57.9	34.1	41.5	39.7	36.1	38.2	
Sd	1.0	1.1	0.7	0.7	1.3	0.3	0.6	0.2	0.6	1.5	0.5	0.3	0.7	0.3	0.4	
RSD	2.6	3.0	2.2	2.1	1.7	0.9	1.5	0.5	1.5	2.6	1.5	0.8	1.8	1.0	1.0	
Expected Value	37.8	39.1	35.7	31.4	78.4	38.3	37.9	38.9	37.4	38.6	34.7	42.7	39.3	36.0	38.4	
%Error	0.4	-3.7	-3.9	1.1	0.8	1.5	1.5	-1.4	-1.8	49.9	-1.8	-2.8	0.9	0.4	-0.6	
NIST 612	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Pb	Th	U
Measured Value	37.6	35.5	37.7	35.8	38.2	36.9	35.8	37.8	38.6	36.4	38.5	36.9	37.2	37.6	38.0	37.4
Sd	0.2	1.3	0.8	0.5	0.9	0.2	0.5	0.5	0.4	0.4	0.4	0.3	0.7	0.7	0.5	0.2
RSD	0.6	3.6	2.1	1.5	2.4	0.6	1.5	1.3	1.1	1.0	1.0	0.8	2.0	1.9	1.3	0.5
Expected Value	37.9	35.5	37.7	35.6	37.3	37.6	35.5	38.3	38.0	36.8	39.2	37.0	36.7	38.6	37.8	37.4
%Error	-0.8	-0.1	-0.1	0.6	2.4	-1.7	0.8	-1.4	1.5	-1.1	-1.9	-0.3	1.3	-2.5	0.5	0.0

Mineral soda-alumina glasses

Seven of the samples were identified as having a high alumina mineral soda composition. All have MgO levels below 1.5% wt which suggests that a mineral alkali, probably reh (a sodic efflorescence found across the Indian subcontinent), was used as the primary flux in their production (see Fig. 3) (Dussubieux et al. 2022; Lankton and Dussubieux 2006). This group is additionally characterised by a high alumina content (>6.5% wt) and elevated soda levels (all except one sample have Na_2O levels > 17.5% wt). Mineral soda high alumina glass (m-Na-Al) is a broad compositional type attested in South Asia and the Indo-Pacific region in glasses beginning in the 1st Millennium BC (Dussubieux 2021). By the time these samples were produced this glass composition is found across a wide geographical range centred around Indian Ocean trade networks, including Southeast Asia, the Islamic World and East Africa (Dussubieux et al. 2008).

The detailed sample descriptions of Manthai m-Na-Al are given in Table 1 of Online Resources. They vary in colour and are artefact types known to have been commonly produced using m-Na-Al glass (Dussubieux et al. 2010). From their compositions it is possible to identify the mineralogical colourants used. Elevated copper levels are seen in MNT 19 (1.2% wt CuO), which is turquoise, as well as MNT 6 (2.5% wt CuO) which is opaque red. Also, there are elevated concentrations of lead (1248 ppm) and tin (386 ppm) in MNT 6 which were probably introduced with the copper in the opaque red glass. MNT 29 is also an opaque sample but is white.

Using data published by Dussubieux et al. 2010; PCA (Principal Components Analysis) was carried out to investigate how Manthai m-Na-Al samples compare with published data using the following discriminating elements: Mg, Ca, Zr, Ba, Sr, U and Cs (Fig. 4). The Manthai m-Na-Al glasses are compared here with known contemporary subtypes including m-Na-Al 1, m-Na-Al 2 glass from Angkor Thom, Cambodia and m-Na-Al 2 glass from Chaul, India. It is clear in Fig. 4 that all the Manthai m-Na-Al glasses are of the m-Na-Al 1 subtype with no overlap with m-Na-Al 2 or m-Na-Al 4. All the m-Na-Al glass from Manthai also exhibit the high barium and low uranium levels which also define this compositional group (see Table 3 above and Table 1 of Online Resource).

The m-Na-Al 1 subtype is abundant in South India and Sri Lanka from the 4th century BC to 5th century AD as well as across Southeast Asia through to the 11th century AD. Its use continues regionally but declines in abundance. At present there is only the site of Giribawa for which there is a possibility that primary glass production occurred, but this is not definite as discussed below in relation to isotopic

Table 3 Means and standard deviations for defined Manthai compositional groups. Only selected oxides (% wt) and elements (ppm) are shown here

Groups	m-Na-Al (*n*=7)	Manthai PA 1 (*n*=3)	Manthai PA 2 (*n*=6)	v-Na-Al (*n*=2)	v-low Mg (*n*=2)	MNT 26
SiO_2	65.1±2.5	72.4±1.3	65.6±1.2	58.3±3.2	65.5±3.8	65.9
Al_2O_3	8.5±1.6	1.2±0.07	2.2±0.3	5.65±0.8	3.6±0	1.9
Fe_2O_3	1.7±0.3	0.4±0.01	1.3±0.6	1.59±0.2	1±0.2	2.4
CaO	2.2±0.6	6.4±0.2	6.1±0.6	8.1±2.5	8.2±2.5	7.5
MgO	0.5±0.2	4.3±0.1	5±0.7	4.9±0.5	3.3±0.5	2.7
Na_2O	18.4±1.7	11.9±0.4	15.2±0.5	17.4±3.6	15.2±0.4	15.5
K_2O	2.2±0.5	2.3±0.3	3.6±0.7	2.6±0.3	2.2±0.3	2.3
P_2O_5	0.08±0.05	0.10±0.01	0.17±0.04	0.31±0.06	0.19±0.05	0.2
Li (ppm)	9±1	19.±1.3	21±3.4	11±6	18±1	32
B (ppm)	37±8	66±1.7	98±11	194±62	112±28	197
Ti (ppm)	4098±1426	370±11.6	676±167	1311±266	902±124	801
V (ppm)	80±15	9±0.8	15±4	21±8	19±3	18
Cr (ppm)	31±7	30±3.4	46±15	105±92	99±6	98
Mn (ppm)	939±1319	7249±2755.4	1698±2638	498±81	4645±4418	6738
Co (ppm)	12±12	6±1.6	376±648	49±42	4±1	2063
Ni (ppm)	15±10	17±2.7	39±25	39±14	30±5	420
Cu (ppm)	4216±7210	27±8.8	2751±4723	7150±7136	24±19	3626
Zn (ppm)	26±12	24±10.6	1632±3354	41±3	30±10	412
Rb (ppm)	43±14	13±1.6	17±4	27±11	16±2	12
Sr (ppm)	314±63	376±72.4	518±61	474±33	519±149	462
Zr (ppm)	585±244	56±5.8	85±27	81±4	58±7	99
Sn (ppm)	71±130	16.±3.1	155±303	113±94	19±4	37
Cs (ppm)	0.4±0.2	0.2±0.02	0.2±0.04	0.23±0.1	0.2±0.005	0.3
Ba (ppm)	1018±307	144±35	135±50	231±41	250±43	387
La (ppm)	32±13	3±0.3	6±1	10±1	7±0.4	8
Ce (ppm)	55±20	6±0.5	12±1	20±2	13±1	15
Hf (ppm)	15±6	1±0.2	2±1	2±0	1±0	3
Pb (ppm)	192±430	42±35	453±964	25±21	3±1	148
Th (ppm)	13±8	1.0±0.01	1.9±0.7	5.21±2.8	1.6±0.2	2
U (ppm)	7±2	0.5±0.007	0.6±0.1	1.3±0.4	0.7±0.2	1

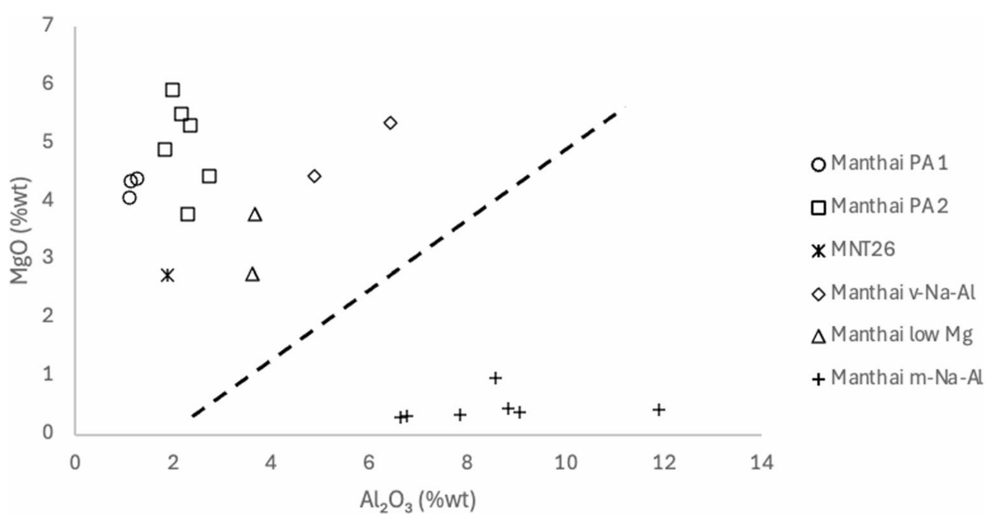


Fig. 3 Biplot of Al_2O_3 vs. MgO (% wt) for all Manthai glass compositional groups showing division between mineral and plant ash soda sources; PA=Plant ash, v=vegetal, m=mineral

evidence. Primary glass production centres across this area may be found in the future and Manthai itself has been posited as one (De Leon et al. 2025; Francis 1991). Francis (1991) discussed bangles and beads being made there between 700 and 1000 AD, supported by the presence of production waste (Trivedi 2021). However, although secondary glass working is known to have occurred at the site there is not yet any scientific or archaeological evidence

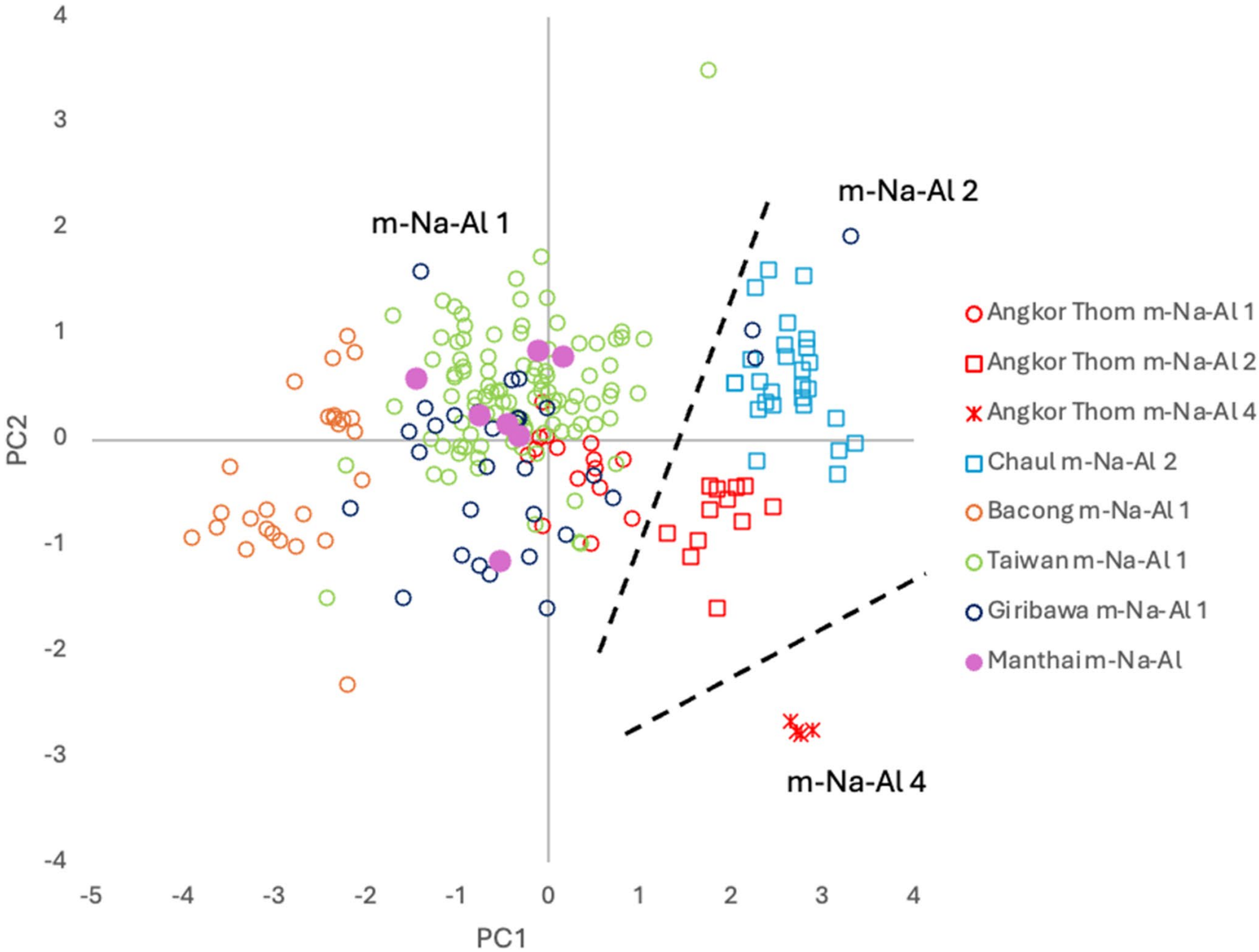


Fig. 4 PCA results for Mg, Ca, Sr, Zr, Cs, Ba and U showing that Manthai m-Na-Al samples belong to the m-Na-Al 1 subtype. Comparative data is from glass samples from m-Na-Al 1, 2 and 4 type glass from Angkor Thom, Cambodia (Carter et al. 2019), m-Na-Al 2 glass samples from Chaul, India (Dussubieux et al. 2008), m-Na-Al 1 glass samples from Bacong, Philippines (De Leon et al. 2025), Taiwan (Wang et al. 2023) and Giribawa, Sri Lanka (Dussubieux 2001)

for primary production. The prevalence of m-Na-Al 1 raw glass at Manthai, including evidence of glass working in a crucible indicates that at Manthai m-Na-Al glass was used to make beads or possibly bangles probably for onward circulation. However, scholars have only relatively recently begun to discuss how abundant m-Na-Al glasses are, especially m-Na-Al 1, across Southeast Asia (Dussubieux et al. 2008; Dussubieux and Gratuze 2010).

Plant ash soda glasses

Fourteen samples can be broadly grouped together based on their plant ash soda source. This is primarily evidenced by their potash and magnesia levels exceeding 1.5% wt and their elevated phosphorus pentoxide levels compared to the mineral soda glasses. By the 8th century AD the use of natron in glass production in the Mediterranean had largely ceased and plant ash glass production became increasingly prevalent (Gratuze et al. 2021; Henderson 2002; Ma et al. 2023). In the period to which the Manthai samples date, plant ashes rich in soda were the most common choice of alkali flux used to make Islamic glass (Freestone 2006; Henderson 2013; Sayre and Smith 1961).

Nine of the Manthai plant ash soda glasses can be split into two groups (PA 1 and PA 2) based on their silica levels and concentrations of associated impurities (Al, Fe, Ti, Zr). The averages and standard deviations for the contents of selected elements in PA 1 and PA 2 can be seen in Table 3. MNT 21, 24 and 25 contain silica exceeding 70% wt and have lower concentrations of alumina and associated impurities (Ti, Zr, Fe) and are referred to here as PA 1 (see Fig. 6). These PA 1 glasses are characterised by very low impurity levels of B, Ti, Cr, Cs, Ba and Hf, and conversely higher silica contents. This suggests that they were produced using a purer silica source than used for Manthai PA 2 (see below) which was specially selected to produce a colourless or very pale product. The selected raw materials are reflected in the appearance of the glasses listed in Table 1 and shown in Fig. 2. Two of the Manthai PA 1 glasses are vessels and the other one is a sample from a tessera. As can be seen in Fig. 5a PA 1 glasses plot with 'Mesopotamian' Type 2 glasses with respect to Al_2O_3 vs. MgO/CaO. Two are colourless and contain MnO in excess of 1% wt, indicating the use of manganese as a decolourant (Gliozzo 2017).

The PA 1 samples share the compositional characteristics of high-quality raw material selection with the Samarra 1 and Nishapur Colourless glasses. They have an average alumina content of 1.2% wt (Fig. 6) and low Zr and Ti. One difference is that while MNT25 has manganese content of 0.5%, lower than required for decolouration, MNT21 and 24 have MnO contents of 1.1% wt and 1.3% wt respectively. This level indicates deliberate addition of MnO for decolourant purposes, also seen in samples from al-Raqqa, part of a standard recipe found in raw furnace glasses (Henderson et al. 2016).

A second group of 6 samples, here referred to as Manthai PA 2, have lower silica (63.7–67.5%) and higher Al_2O_3 and other associated impurities (Fe, Zr, Ti) reflecting the use of a less pure silica source (Fig. 6). It is likely that PA 1 glass was made with crushed quartz pebbles and PA 2 with quartz-rich sands. They also contain higher potash than the glasses in PA 1 (Table 3; Fig. 11). PA 2 glasses have a wider compositional range than PA 1. The glass type plots broadly with 'Mesopotamian' Type 2 glasses, with two plotting amongst 'Mesopotamian' Type 1 in Fig. 5a.

PA 2, which are mainly raw glasses, are variously coloured as noted by Siu et al. (2023). They include blue raw glass coloured by cobalt (MNT 14), pale green MNT 5, aqua MNT 17 and the green glaze of MNT 18; the latter 3 are 'naturally' coloured. There are also two opaque red samples (MNT 20 and 23). The copper droplets present in MNT 20 produce an opaque red colour, with the presence of reduced iron to produce the red hue. This is evidenced by the elevated concentration of iron and conversely lower concentrations of antimony (other elements which could be present as reducing agents) (Mirti et al. 2002). The elements responsible for the opaque red colour of MNT 23 are less clear – Pb levels are only slightly higher than the transparent glasses of the same group at 72ppm, compared to MNT 20 which contains Pb at 2609ppm. There is no elevation in CuO or SnO_2. However, a combination of elevated MnO and lower Fe_2O_3 in a reducing furnace atmosphere could produce this colour (Henderson 1985).

Another distinction between PA 1 and PA 2 glasses (and also 'Mesopotamian' Type 1 and 2) is their P_2O_5 concentrations (see Table 3). In both cases the group made using a purer silica source (Manthai PA 1 and 'Mesopotamian' 2) also exhibit lower P_2O_5 concentrations (Schibille et al. 2018; Siu et al. 2023).

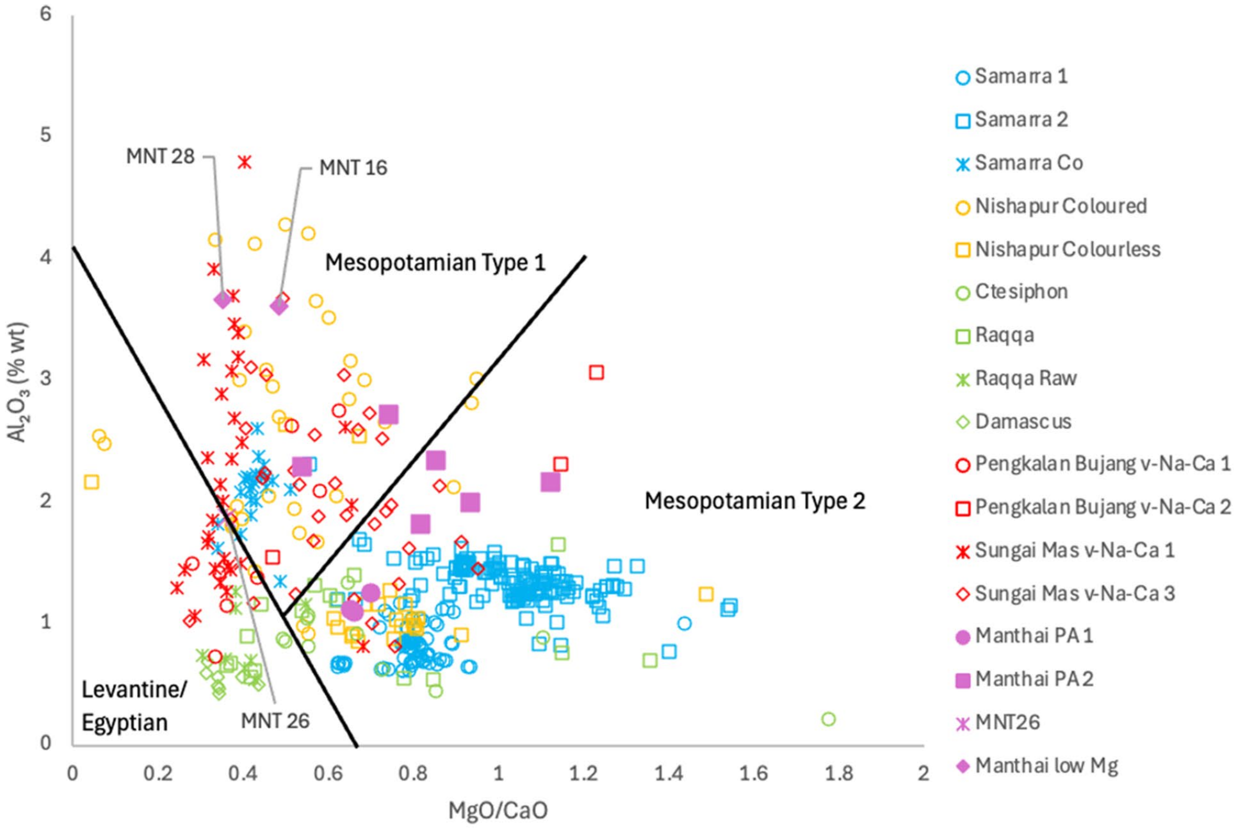
One other plant ash glass, MNT 26, a cobalt blue bottle fragment, plots closer to 'Levantine/Egyptian' glasses. This provenance can be attributed to higher CaO and lower MgO concentrations in MNT 26 compared to higher MgO in Manthai PA 1 and 2 glasses.

Other plant ash glasses: v-Na-Al and low Mg

MNT 7 and 27 contain high Al_2O_3 concentrations (6.42% wt and 4.89% wt respectively); MNT 27 also contains a high lime concentration: 10.59% wt. They are referred to here as v-Na-Al. MNT16 and 28 (referred to here as Manthai low Mg) contain between 3 and 4% wt Al_2O_3 and notably lower MgO and K_2O contents compared to PA 1 and PA 2 glasses (2.8–3.8% wt MgO compared to 3.8–5.9% wt MgO and 1.8–2.5% wt K_2O compared to 1.9–4.3% wt K_2O respectively- see Tables 1 and 3 of the Online Resources; MNT 28 also contains high lime (10.76% wt). As will be discussed later, even though the two Manthai low Mg glasses plot in the 'Mesopotamian' Type 1 area in Fig. 5a, this does not definitively show they are of a 'Mesopotamian' origin.

In Fig. 5a the low Mg samples plot close to some high Al_2O_3 glasses in the Nishapur coloured group and some of the v-Na-Ca glasses from Pengkalan Bujang and Sungai Mas, Malaysia. Figure 5b shows compositional similarities between MNT 7 and the v-Na-Al samples from Pengkalan Bujang while MNT 27 plots closely with glasses from Iran and Central Asia.

Due to multiple possible provenances of the Manthai v-Na-Al and low Mg glasses, additional comparisons were considered necessary. v-Na-Al type glasses are known from sites across Central Asia as well as Eastern and Southern Africa, Southeast Asia and Egypt. However, their compositions differ from glasses found across these regions. Initial PCA was conducted including samples from all these regions which showed the Manthai v-Na-Al samples (MNT 7 and 27) to be compositionally most similar to glasses from Central Asia and Malaysia. For this reason, PCA for the same elements and ratios was conducted focussing on Central Asian glasses and glasses from Pengkalan Bujang and Sungai Mas, since these Malaysian glasses are believed to come from the Islamic Middle East (Dussubieux and Allen 2014). The PCA plot is presented in Fig. 7.


MNT 28
MNT 16
Mesopotamian Type 1
Mesopotamian Type 2
Levantine/
Egyptian
MNT 26
Al_2O_3 (% wt)
MgO/CaO
Samarra 1
Samarra 2
Samarra Co
Nishapur Coloured
Nishapur Colourless
Ctesiphon
Raqqa
Raqqa Raw
Damascus
Pengkalan Bujang v-Na-Ca 1
Pengkalan Bujang v-Na-Ca 2
Sungai Mas v-Na-Ca 1
Sungai Mas v-Na-Ca 3
Manthai PA 1
Manthai PA 2
MNT26
Manthai low Mg

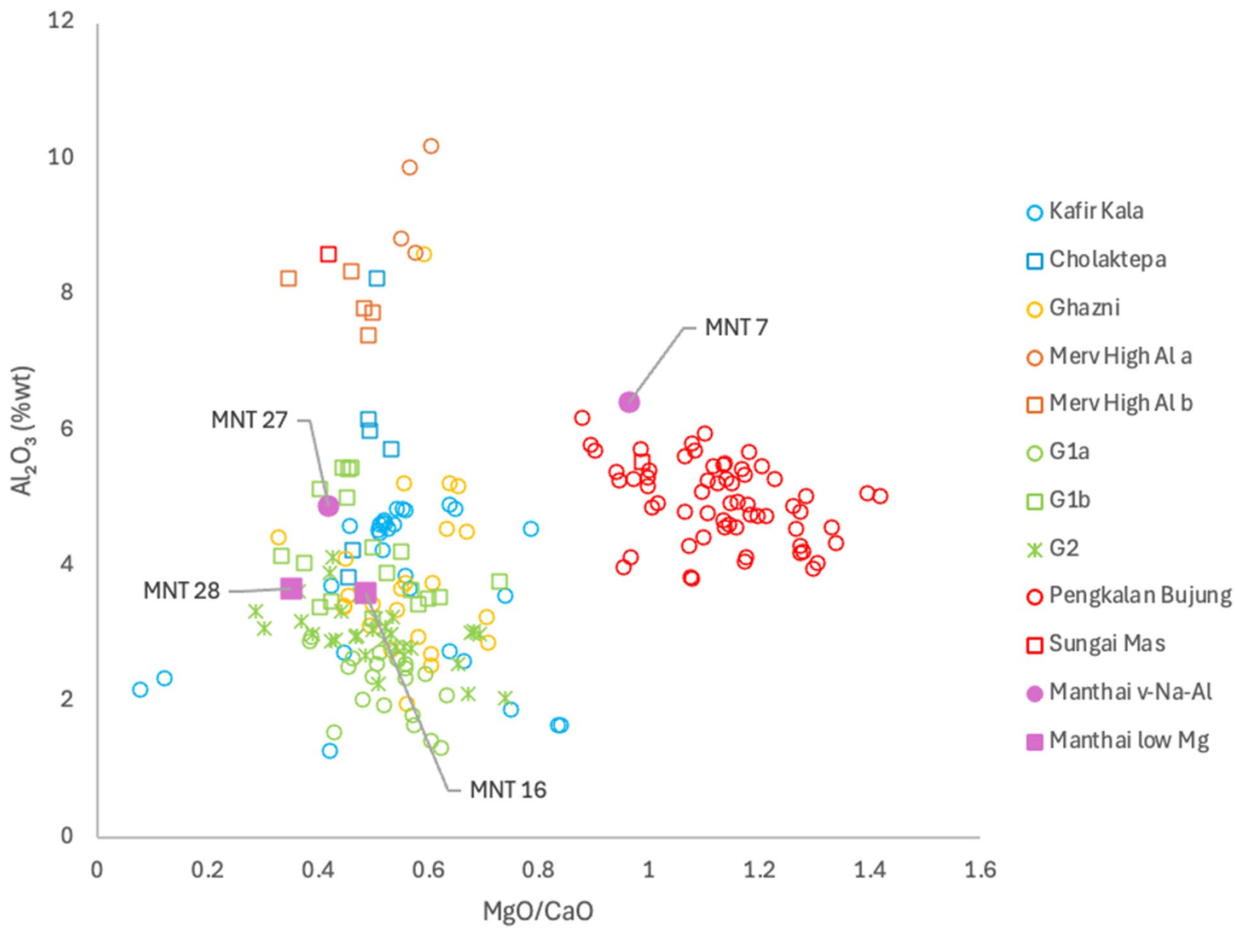

MNT 7
MNT 27
MNT 28
MNT 16
Al_2O_3 (%wt)
MgO/CaO
Kafir Kala
Cholaktepa
Ghazni
Merv High Al a
Merv High Al b
G1a
G1b
G2
Pengkalan Bujung
Sungai Mas
Manthai v-Na-Al
Manthai low Mg

Fig. 5 **a** and **b** Biplots of Al_2O_3 vs. MgO/CaO for (a, above) the Manthai plant ash glass samples (except Manthai v-Na-Al glasses) compared to glasses from Samarra, Iraq (Schibille et al. 2018), Nishapur, Iran (Wypyski 2015), Ctesiphon, Iraq, al-Raqqa and Damascus, Syria (Henderson et al. 2016) and v-Na-Ca glasses from Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014) and (b, below) Manthai v-Na-Al and low Mg samples compared to samples from Kafir Kala and Cholaktepa, Uzbekistan (Chinni et al. 2023), Ghazni, Afghanistan (Fiorentini et al. 2019), Merv, Turkmenistan (Meek et al. 2025), various sites in Iran (Schibille et al. 2022) and v-Na-Al glasses from Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014)

Discussion

Mineral soda alumina glasses: m-Na-Al

Multiple sub-types of m-Na-Al glass have been identified and have been distinguished by other researchers particularly by their minor oxide and trace element contents, notably levels of MgO, CaO, Sr, Zr, Cs, Ba and U (Dussubieux et al. 2010). The average and standard deviations for the contents of these elements and oxides for the Manthai m-Na-Al glasses can be seen in Table 3.

The trace element compositions of Manthai m-Na-Al samples, especially the Ba and Cs concentrations overlap with known m-Na-Al sub-type 1 compositions (Dussubieux et al. 2010). This sub-type is commonly found at South Indian and Sri Lankan sites from the 4th century BC – 5th century AD. It is also well attested at sites across Southeast Asia into the mid-2nd Millennium AD (Dussubieux et al. 2010). Glass working and possible evidence for primary glass production of m-Na-Al 1 has been found at the site of Giribawa, Sri Lanka dating to the 3rd century BC – 2nd century AD but no definitive archaeological evidence for primary glass production, such a semi-fused glass (frit), has been found (Rolland et al. 2023). Previous unpublished analyses have also linked the m-Na-Al 1 sub-type to Manthai (Walder and Dussubieux 2022). Primary glass production refers to the fusion of raw glass from raw materials whereas secondary glass production refers to the remelting of raw glass to form glass objects (Henderson 2013, 18–21). The presence of raw glass supports the possibility of secondary glass working at Manthai but does not constitute proof that primary production occurred there.

m-Na-Al glasses are among the most common glass compositional types found in South Asia. They are also found in Southeast Asia and Southern and Eastern Africa throughout the 1st Millennium AD, transported via the Indian Ocean maritime trade routes. Figure 8 shows the PCA results of Manthai m-Na-Al samples compared with the site of Giribawa, Sri Lanka and contemporary m-Na-Al 1 glasses from Southeast Asia. These results show a lack of overlap with the samples from Giribawa which, it has been suggested, was a site of primary production for m-Na-Al 1 glass but in a time period prior to the date attributed to the Manthai glasses (Dussubieux et al. 2010). Indeed, the Manthai m-Na-Al 1 samples are more similar to glasses from Cambodia, the Philippines, Taiwan and Malaysia – all of which have coastlines on the South China Sea.

The PCA results shown in Fig. 8 indicates a connection in terms of glass movement between Manthai and the South China Sea, which is of interest considering that the South China Sea region is generally understudied in the discourse on regional glass exchange. It is made more interesting by the fact that no m-Na-Al 1 glass waste is present in any of the Southeast Asian assemblages that have been studied (Carter et al. 2019; De Leon et al. 2015; Dussubieux and Allen 2014; Wang et al. 2023). This suggests that the Manthai m-Na-Al glasses were intended to be used in making artefacts such as beads or bangles for export by maritime trade to Southeast Asia. There is the additional possibility that these raw glasses were destined to be shipments to East and Southeast Asia where they would be remelted into objects. This interpretation is less likely when the evidence for secondary production using m-Na-Al 1 glass at Manthai is considered, both considering the glass studied here and as presented by Francis (1991) and Trivedi (2021). There is also no evidence in Southeast Asia for secondary production using m-Na-Al 1 glass (Wang et al. 2023). This supports the idea that Manthai was more than a site simply exporting or transhipping m-Na-Al 1 eastwards but was actively involved in producing objects to supply maritime trade with the South China Sea region.

These results do not however answer the question of where this m-Na-Al 1 glass was originally fused from primary raw materials. Isotopic analysis of m-Na-Al 1 samples from Giribawa and Angkor Borei, Cambodia have indicated a difference in their Sr and Nd ratios. The Giribawa glass (and 2 'raw material') samples generally have higher ε_{Nd} values, comparable geologically with the northwestern part of Sri Lanka where Giribawa is located (Dussubieux et al. 2021, 2025). Nevertheless, isotopic results for geological samples from Sri Lanka, southern India and Malaysia overlap with ε_{Nd} values at around −20 and $^{87}Sr/^{86}Sr$ values of between 0.710 and 0.715 (Dussubieux et al. 2021, 2025). Thus, the glass may potentially have been made locally. But the results do not yet prove that the glass was definitely fused at Giribawa. In addition to discovering frit, a more comprehensive isotopic investigation would involve comparing the isotope signatures for Giribawa and Manthai glass with those determined for raw materials from the environment near Giribawa and Manthai along geological transects across broader contrasting geological zones across the landscape. These are known as isoscapes, such as those published by Lü et al. (2023) and Henderson et al. (2020).

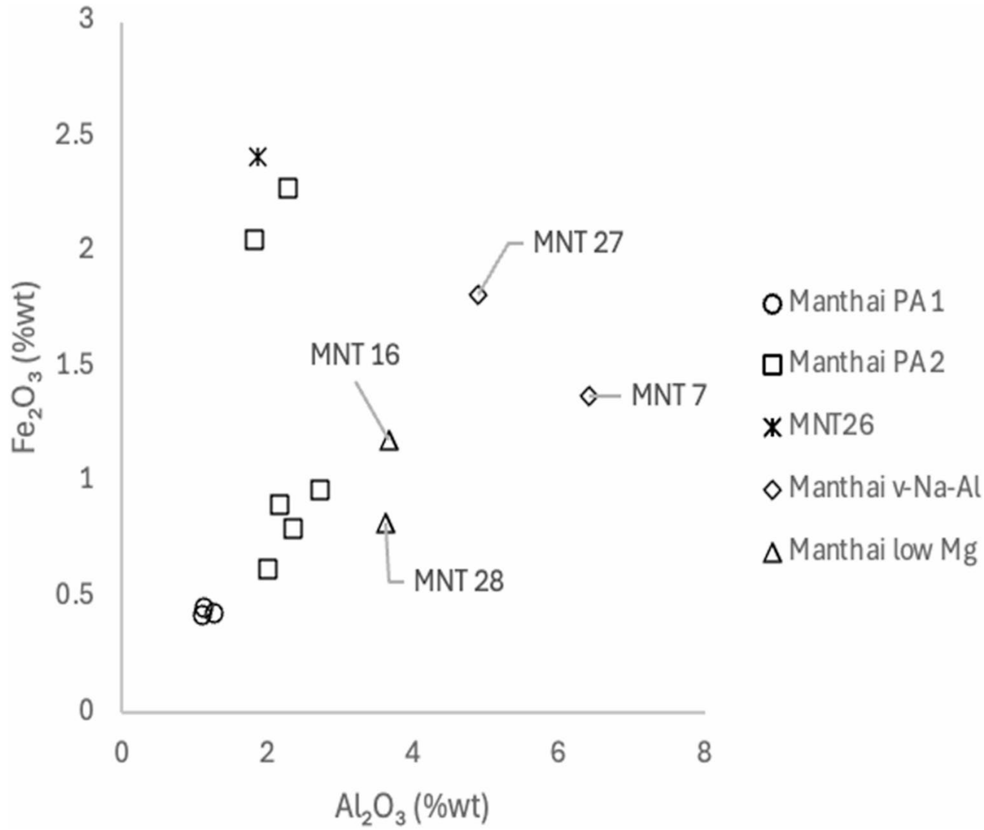


Fig. 6 Biplot of Al_2O_3 vs. Fe_2O_3 of Manthai plant ash soda glasses showing variations of the purity of silica source

From the results presented in Fig. 8 Manthai and Giribawa m-Na-Al glasses are sufficiently different to be able to state that Manthai glasses were not made at Giribawa, if indeed primary glass production occurred there. Hopefully, future isotopic analyses combined with trace element analyses of Manthai glasses should help to clarify whether primary production occurred at Manthai. What is clear from our results is that the role of Manthai in provisioning glass for the Maritime Silk Roads is not limited to transhipment. These raw glass samples and evidence for secondary production activity show those living at Manthai in the late 1st millennium to have been engaged in producing objects for trade. The consumption of such products in Southeast Asia and around the South China Sea shows how the Manthai m-Na-Al 1 glasses represent exchange and trade within the Indian Ocean region.

Further compositional comparisons of Manthai plant Ash glasses with other West Asian plant ash glasses

In order to investigate further the provenances of Manthai plant ash glasses they were compared using a PCA plot with data from 9th −10th century Samarra, Iraq, Nishapur, Iran, al-Raqqa, Syria (a site where primary glass production occurred on a massive scale), Ctesiphon, Iraq and 11th −12th century Damascus, Syria. Samples from 11th −14th century Pengkalan Bujang and 6th −13th century Sungai Mas, both in Malaysia, were also included as these sites have yielded a similar variety of glass compositions to the Manthai samples (see above). The results of this PCA using Na, Mg, Al, Ca, Fe, Ti, Sr, Zr and Cr/La ratios can be seen in Fig. 9.

The PCA shows a clearer distinction between Manthai PA 1 and 2 groups (and the cobalt blue MNT 26) than in Fig. 5a. The PA 1 data plots closely to Samarra glasses and PA 2 with Nishapur glasses. Within the glasses from Samarra, Nishapur and Manthai there is a group of colourless or pale green glasses, a larger group of variously coloured glasses with higher impurity levels and cobalt blue bottles. The latter, of which MNT 26 is an example, plot alongside glasses of Levantine or Egyptian origin as noted above (Fig. 5a). Samples from these bottles exhibit elevated levels of boron and lower cobalt-zinc ratios compared to 'Mesopotamian' cobalt blue glasses (Schibille et al. 2018). From the PCA results in Fig. 9 and similarities observed in Fig. 5a it can be suggested that MNT 26 shares an origin with the cobalt blue bottles found at Ramla and Samarra. These are considered to have a 'Mesopotamian' origin, shared with those found at Samarra, because of their Zr and Ti values and Cr/La ratios as opposed to the Levantine or Egyptian origin that Fig. 5a might suggest

Fig. 7 PCA results for Na, Al, Rb, Zr, La, Hf and Th comparing Manthai v-Na-Al and low Mg glasses to samples from Kafir Kala and Cholaktepa, Uzbekistan (Chinni et al. 2023), Ghazni, Afghanistan (Fiorentini et al. 2019), Merv, Turkmenistan (Meek et al. 2025), various sites in Iran (Schibille et al. 2022) and v-Na-Al glasses from Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014)

(see Fig. 10) (Phelps 2018). Fragments of more of these distinctive bottles have been found in Eastern Africa and China. Therefore, the presence of the cobalt blue bottle at Manthai along with its potential contents, adds to the evidence for their circulation throughout the Indian Ocean world (Foy 2012; Phelps 2018).

As shown in Figs. 5a, 9, and 10, and 11 there are many similarities between Manthai PA 1 and 2, Samarra 1 and 2 and Nishapur Colourless and Coloured glasses including their Zr/Ti and Cr/La ratios. This confirms their 'Mesopotamian' origin as already suggested by their Al_2O_3 vs. MgO/CaO values (Fig. 5a). It is already known that the glasses from the Islamic world such as those made at al-Raqqa and found at Samarra were produced by deliberate and established production strategies by people knowledgeable and experienced enough to tightly control the glass making process to produce a specific and consistent product (Henderson et al. 2004; Henderson 2013, 2022; Schibille 2022; Schibille et al. 2018), leading to decentralised production focused in cosmopolitan hubs across western and central Asia (Henderson et al. 2016; Henderson 2022). Manthai has therefore benefitted from this high volume of production. Moreover, it can be suggested that there would have been a range of glass qualities, some being made with purer or more unusual raw materials and other with slight contamination possibly leading to compositional variations between batches made on the same industrial estate.

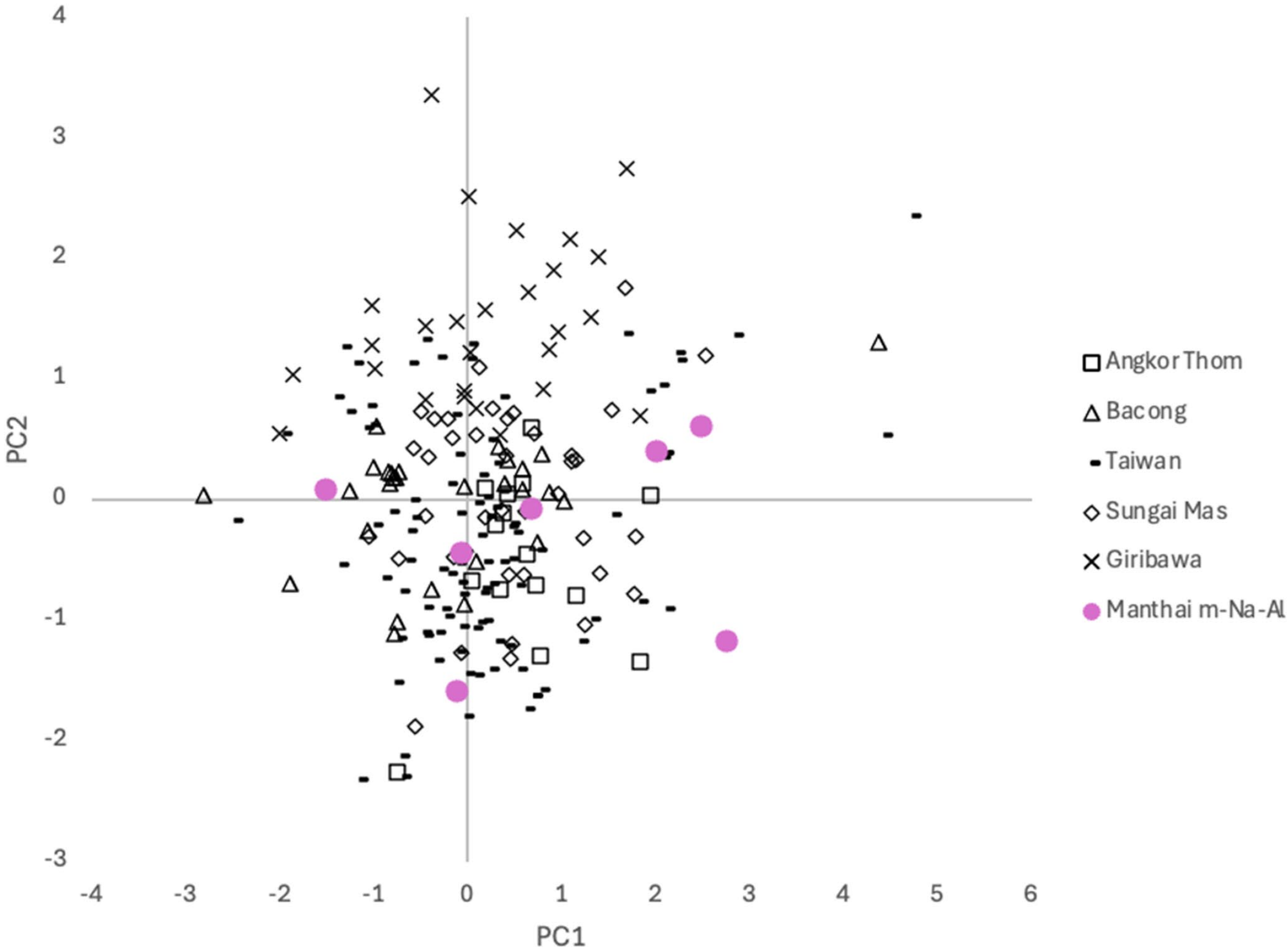


Fig. 8 PCA results for Na, Al, Rb, Zr, La, Hf and Th in Manthai m-Na-Al samples compared to known m-Na-Al 1 samples from Angkor Thom, Cambodia (Carter et al. 2019), Bacong, Philippines (De Leon et al. 2025), Taiwan (Wang et al. 2023), Sungai Mas, Malaysia (Dussubieux and Allen 2014) and Giribawa, Sri Lanka (Dussubieux 2001)

v-Na-Al plant ash glasses

The PCA results seen in Fig. 7 indicate differing geographical origins for the two Manthai v-Na-Al samples. MNT 7, a pale green vessel base, plots more closely with high Al_2O_3 glasses from Merv, which it has been suggested derive from eastern Central Asia (Meek et al. 2025). The idea of a Central Asian provenance for MNT 7 is supported by the data displayed in Fig. 10 with MNT 7 having a Cr/La ratio of 1.2. This very low Cr/La ratio distinguishes MNT 7 from glasses of 'Mesopotamian' origin while its high MgO content (and Al_2O_3 of 6.42% wt) precludes it from having a Levantine or Egyptian origin (Schibille et al. 2022; Siu et al. 2023). In addition to its Cr/La ratio, elevated Na_2O, B (255.11 ppm) and P_2O_5 contents support a Central Asian origin (see Table 1 of Online Resource) (Lü et al. 2023). MNT 27, an emerald green bowl, overlaps with the G1a and b groups from Iran in Fig. 7 which are thought to have been produced in Central Asia and/or on the Iranian plateau, east of the Zagros Mountains (Schibille et al. 2022). There are, however, aspects of the composition of MNT 27 which suggest that a Central Asian origin is unlikely, including its much higher Cr/La ratio compared to MNT 7 and known Central Asian glasses (see Fig. 10). MNT27 is more difficult to assign a regional provenance. Its higher Cr/La ratio suggests it could originate from 'Mesopotamia' but its higher P_2O_5, slightly elevated B, high Al_2O_3 (4.89% wt) and low MgO/CaO contents (Figs. 5b, 10 and 11 and Table 1 of Online Resource) could indicate a Central Asian origin (Barkoudah and Henderson 2006; Schibille et al. 2024).

Low Mg plant ash glasses

In the Fig. 7 PCA results for both MNT 16 (dark green appearing 'black' raw glass) and MNT 28 (pale olive-green flask fragment) overlap broadly with samples from Kafir Kala and Cholaktepa, Uzbekistan and Ghazni, Afghanistan. Initially their elevated Cr/La ratios would appear to exclude

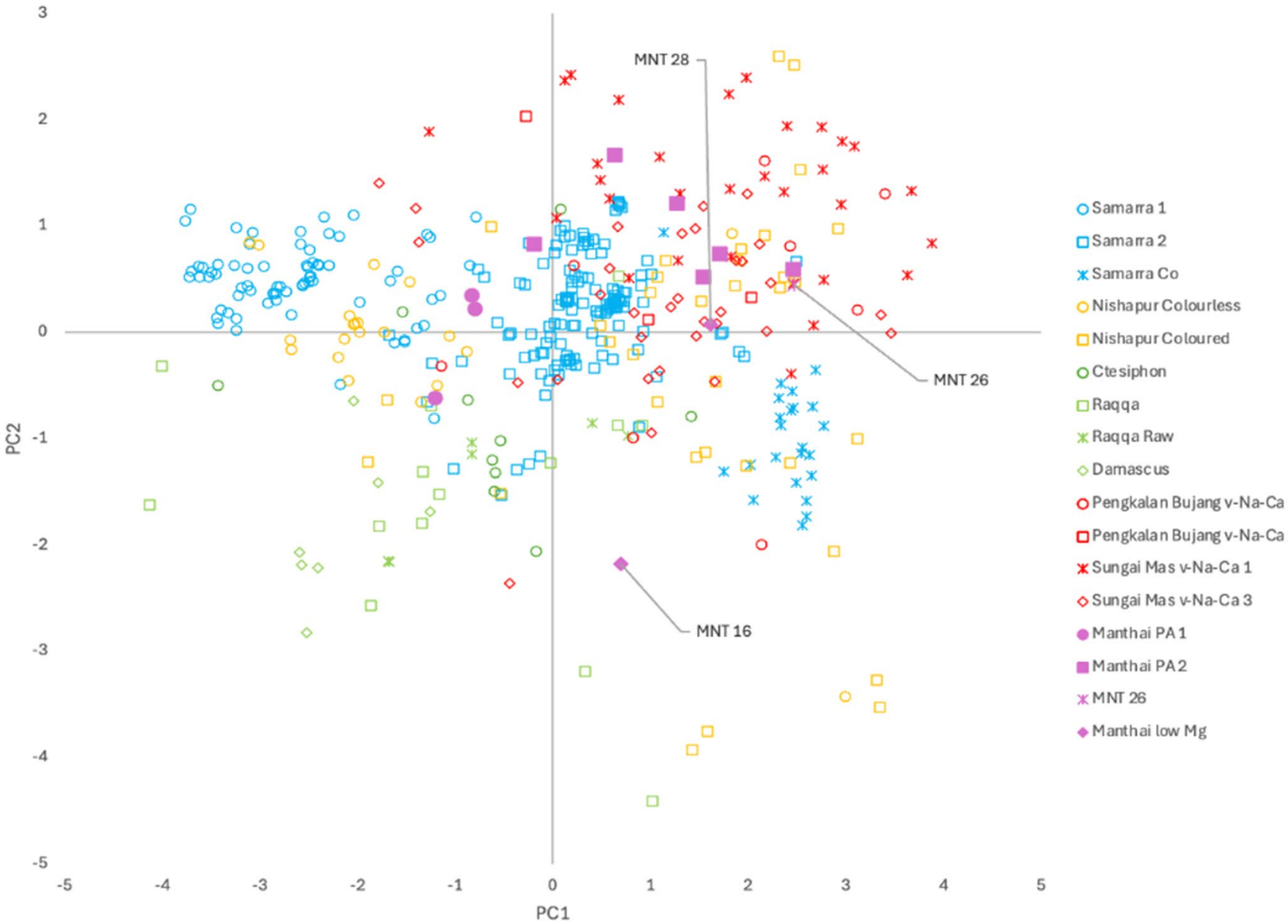


Fig. 9 PCA results for Na, Mg, Al, Ca, Fe, Ti, Sr, Zr and Cr/La in Manthai PA 1 and 2, MNT 26 and low Mg glasses compared to samples from Samarra, Iraq (Schibille et al. 2018), Nishapur, Iran (Wypyski 2015), Ctesiphon, Iraq, al-Raqqa and Damascus, Syria (Henderson et al. 2016) and Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014)

the idea of these glasses having a Central Asian provenance and suggest them to be of 'Mesopotamian' origin (Siu et al. 2020, 2023). However, within the Kafir Kala and Cholaktepa samples a sub-group of glasses with elevated Cr/La ratios comparable to those found in the Ctesiphon glasses was identified which can be seen to overlap with the Manthai low Mg samples in Fig. 10 (Group C, Chinni et al. 2023). MNT 16 and 28 also display elevated Al_2O_3 concentrations (c. 3.6% wt) compared to glasses classified as 'Mesopotamian' in Fig. 5a. In Figs. 5a and 10 there are similarities between the Manthai low Mg samples and coloured Nishapur glasses with high Al_2O_3 concentrations and elevated Cr/La ratios. MNT 16 is more likely to be of Central Asian origin as opposed to 'Mesopotamian' since it plots separately from 'Mesopotamian' samples in Fig. 9 and it does not fit the V versus Cr correlation in Fig. 12 (Meek et al. 2025). In addition, MNT 16 contains only 0.14% wt P_2O_5 (see Fig. 11) compared to the Samarra 2 and Nishapur Coloured glasses which generally contain around 0.3% wt allowing us to attribute MNT 16 to a Central Asian provenance (Schibille et al. 2022; Wypyski 2015). Conversely MNT 28 contains a slightly higher concentration of P_2O_5 (0.24% wt) and plots alongside Samarra 2 and Nishapur Coloured samples in the PCA results seen in Fig. 9.

The archaeological significance of the variety of plant ash glasses from Manthai

The plant ash soda glasses from Manthai presented here are varied both in their compositions and the artefacts that were made from them. The Manthai PA 1 and 2 samples represent a division in glasses imported from the Abbasid Islamic world with the former being a small sub-group of finished objects and the latter being composed of mostly raw glasses. Manthai PA 1 glasses were likely produced at or proximally to Samarra using specifically selected raw materials to produce specific artefact types which represent a technical regional specialisation (Henderson et al. 2016; Schibille et al. 2018). The composition of the cobalt blue bottle (MNT 26) supports the idea of finished products from decentralised

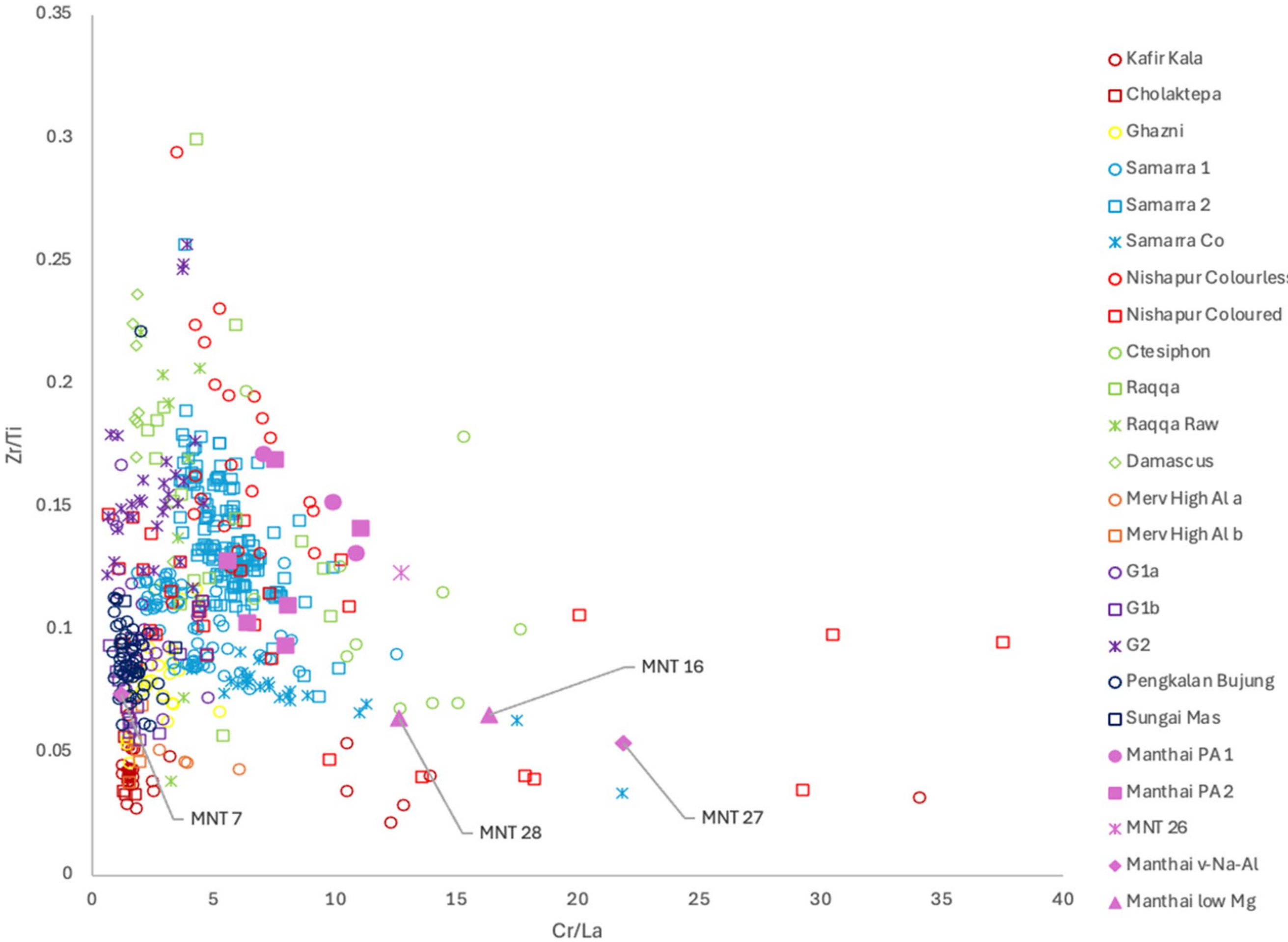


Fig. 10 Biplot of Cr/La vs. Zr/Ti for Manthai plant ash glasses compared to samples from Samarra, Iraq (Schibille et al. 2018), Nishapur, Iran (Wypyski 2015), Ctesiphon, Iraq, al-Raqqa and Damascus, Syria (Henderson et al. 2016) Kafir Kala and Cholaktepa, Uzbekistan (Chinni et al. 2023), Ghazni, Afghanistan (Fiorentini et al. 2019), Merv, Turkmenistan (Meek et al. 2025), various sites in Iran (Schibille et al. 2022) and v-Na-Al glasses from Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014)

production centres in the Abbasid world (Henderson et al. 2016) being exported to Manthai. Glass objects of Middle Eastern origin have been found at sites partly contemporary with Manthai in Southeast Asia, such as Pengkalan Bujang and Sungai Mas in Malaysia (Dussubieux and Allen 2014) and in China (Li et al. 2016). There is also evidence from shipwrecks including the Belitung and Cirebon in the South China Sea attesting to trade including glass products between Southeast Asia and the Abbasid Middle East (Henderson et al. 2021). As an established node of transhipment on the Maritime Silk Road between the Abbasid world and Southeast and Eastern Asia via the South China Sea the compositions of these glasses exemplify a facet of the role of Manthai in glass provisioning. The demand for specific kinds of luxury glassware in the east, as exemplified by the large amounts of glass found on the 10th century Cirebon shipwreck (Swan Needell 2018), was being met via maritime transhipment at Indian Ocean ports including Manthai.

The presence and composition of Manthai PA 2 glasses suggest a continuation of the export of raw glasses from Islamic glassmaking centres in the 9th to 11th centuries. This appears to conflict with the assertion by Meek et al. (2025) that this had largely ceased by the 9th century. Due to the small sample size of the Manthai PA 2 glasses it cannot be claimed that this constitutes solid evidence for this practice continuing on a large-scale but it does indicate that raw 'Mesopotamian' glasses were arriving at Manthai in this period. As discussed above in relation to the Manthai m-Na-Al samples, there is evidence for at least secondary glass production at the site - although not for raw glasses of the Manthai PA 2 type. It is possible that the intention was to use PA 2 glass to make objects at Manthai. The other likely intended use of the raw Manthai PA 2 glasses is for export eastwards for secondary production in Southeast Asia. Glass waste was found at Sungai Mas of a similar composition, believed to originate from the Middle East but the evidence

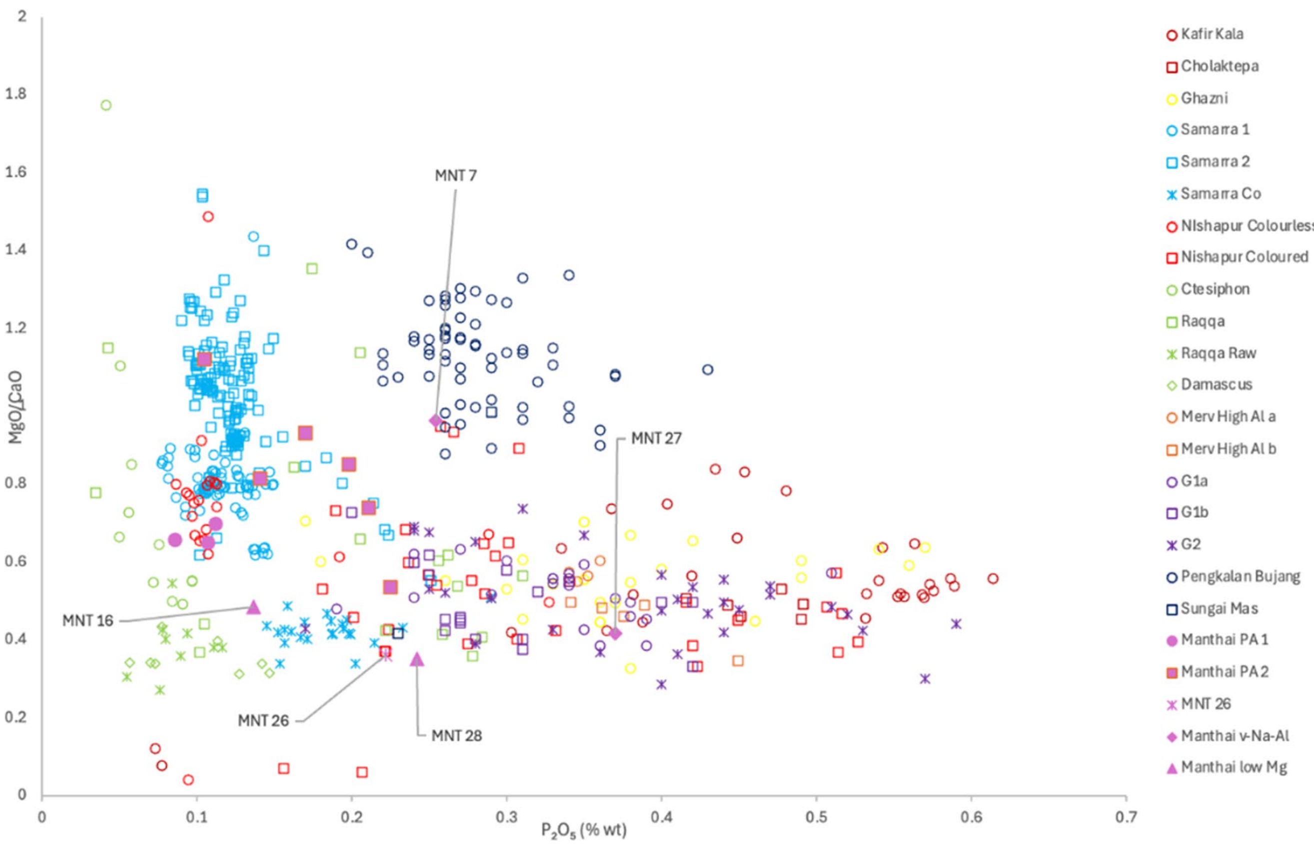


Fig. 11 Biplot of P_2O_5 vs. MgO/CaO for Manthai plant ash glasses compared to samples from Samarra, Iraq (Schibille et al. 2018), Nishapur, Iran (Wypyski 2015), Ctesiphon, Iraq, al-Raqqa and Damascus, Syria (Henderson et al. 2016) Kafir Kala and Cholaktepa, Uzbekistan (Chinni et al. 2023), Ghazni, Afghanistan (Fiorentini et al. 2019), Merv, Turkmenistan (Meek et al. 2025), various sites in Iran (Schibille et al. 2022) and v-Na-Al glasses from Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014)

for the use of Islamic glass in this way in Southeast Asia is generally scant (Dussubieux and Allen 2014). The presence of raw plant ash glass at Manthai adds to the evidence of the provisioning of a variety of glasses and products to the Southeast and East Asian markets and is a reflection, at distance, of highly organised Islamic primary and secondary glass production in cosmopolitan hubs across western (and central) Asia. The location of Manthai is especially significant for Indian Ocean trade between east and west, including well before the period under discussion here (Kingwell-Banham et al. 2018). It is interesting to consider why plant ash glass was imported rather than being fused from raw materials on Sri Lanka. Even though alkali-rich halophytic plants grow there, including of the genus Salicornia (Siridewa et al. 2025), this would not necessarily have led to this glass type being made there, for a range of complex social and technological reasons (Henderson in press).

MNT 7 (Manthai v-Na-Al), a green vessel fragment and MNT 16 (Manthai low Mg) raw glass probably derived from Central Asia; MNT 28 may have come from the same region. This expands our view of Manthai as a site of prominence in the provisioning of glass and facilitating its movement along not only the Maritime Silk Road but also along the long-distance overland networks spanning Eurasia (Henderson 2024; Lü 2024).

Conclusions

The results of our LA-ICP-MS analyses confirm the division of the Manthai samples into glasses made using an alumina rich mineral soda source either in South Asia or Sri Lanka, possibly at or near Manthai itself and those made using halophytic soda rich plant ashes imported from the Islamic Middle East.

All of the mineral soda glasses belong to the m-Na-Al 1 subtype based on their high barium and low uranium contents, which was believed to be more common in this region before the 5th century AD but remained prevalent in Southeast Asia until the 11th century (Dussubieux and Geria 2024). Although Manthai has been posited as a site of primary glass working for m-Na-Al 1 (Buddikasiri and Madhumali 2020; Selvakumar 2021), this cannot be confirmed based solely on the results presented here. With the majority

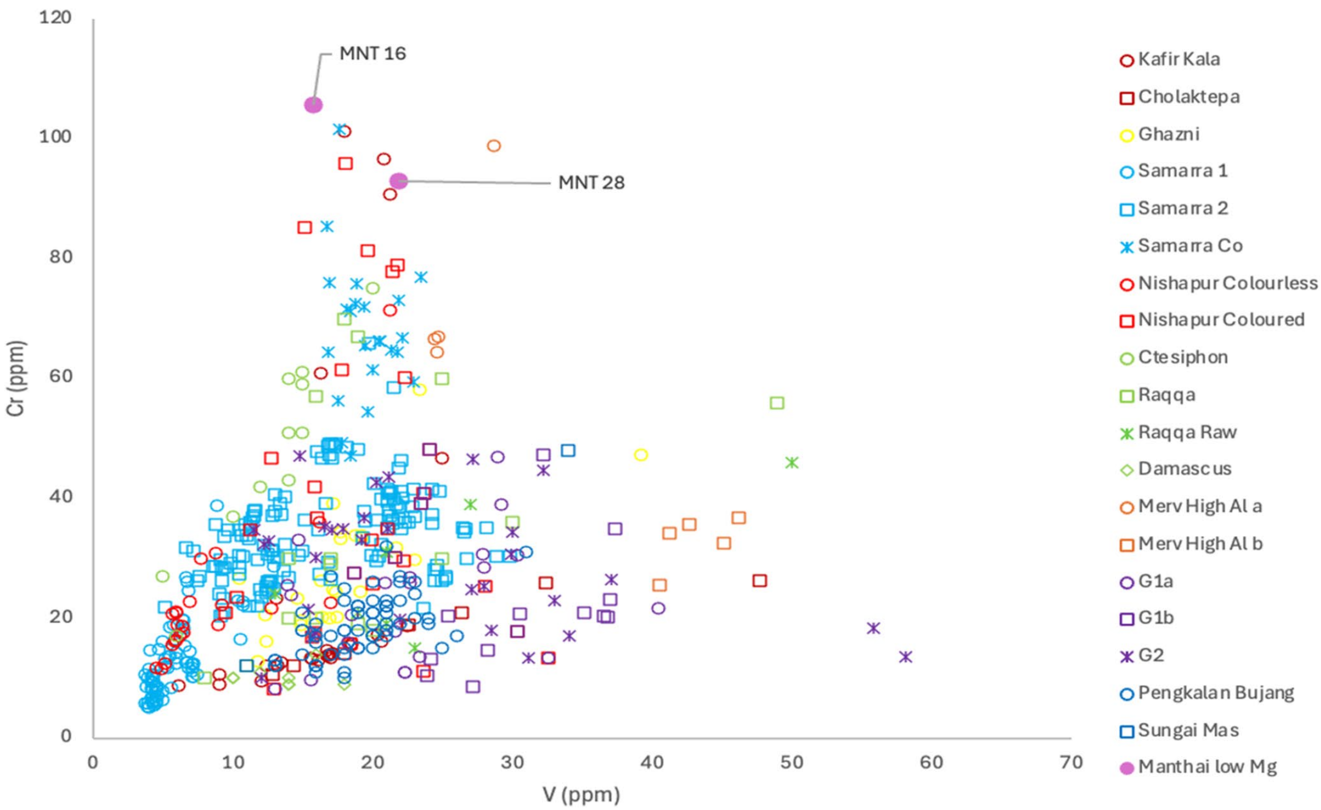


Fig. 12 Biplot of V vs. Cr (ppm) for Manthai low Mg samples compared to Samarra, Iraq (Schibille et al. 2018), Nishapur, Iran (Wypyski 2015), Ctesiphon, Iraq, al-Raqqa and Damascus, Syria (Henderson et al. 2016) Kafir Kala and Cholaktepa, Uzbekistan (Chinni et al. 2023), Ghazni, Afghanistan (Fiorentini et al. 2019), Merv, Turkmenistan (Meek et al. 2025), various sites in Iran (Schibille et al. 2022) and v-Na-Al glasses from Pengkalan Bujang and Sungai Mas, Malaysia (Dussubieux and Allen 2014)

of Manthai m-Na-Al 1 samples being raw glass, including a piece of crucible glass, it contributes to our understanding of secondary glass production at the site. Evidence for secondary production of m-Na-Al 1 glass at Manthai, the abundance of compositionally similar m-Na-Al 1 glass in contemporary Southeast Asia and the lack of secondary glass working evidence in Southeast Asia indicates Manthai had a role in both producing and transporting m-Na-Al 1 products to the South China Sea area. Thus, it can be claimed that the site provided both glasses for the Maritime Silk Roads, acting as a site of transshipment, and for making objects for inter-regional trade.

The plant ash soda glasses are more diverse in composition and geographic origin than the mineral soda glasses, with the majority of samples forming two sub-groups identified as being of the Samarra 1 and 2 types. These constitute a small group of high-quality colourless and pale green glasses specifically produced using selected raw materials as well as a larger quantity of variously coloured glasses made using less pure raw materials respectively. The latter subgroup (Manthai PA 2) consists entirely of raw glass samples, a finding which has implications for our understanding of the decentralised system in which they were produced. There are additionally at least two plant ash soda glass samples from Manthai which have been shown to have been made in Central Asia and which differ from each other in terms of composition. The role of Manthai in transhipment has been known prior to this but these glasses highlight the extent and variety of glassmaking regions the site was connected to and the types of glass the site was provisioning for onwards transport to the east. The raw glasses found here with origins in the Islamic Middle East with the evidence at Manthai for secondary glass production raises the question of whether only m-Na-Al 1 glass was used to form objects at the site. It is hoped that future work investigating glass working evidence at Manthai will shed further light on this.

The glasses presented here reflect the multiple roles the site of Manthai played in provisioning glasses for the Silk Roads. They show the site and its occupants as engaged in secondary working and export of regional mineral soda alumina glass for the Southeast Asian market, focused on trade in the South China Sea. This was likely also the intended destination for the plant ash glasses with a variety of compositions produced in the Islamic Middle East and Central Asia found at Manthai also being present on Southeast Asian sites. This shows that in the 8th to 13th centuries Manthai was a prominent Silk Road port emporium engaged in multi-faceted activities related to vitreous materials. Manthai is therefore a site connected and enmeshed in commercial long-distance trade networks across sea and land where glasses of multiple forms and compositions were gathered from various Western Asian and Central Asian origins to supply products for local consumption and for use in craft production on regional, inter-regional and supra-regional scales along the Eurasian Silk Roads (Henderson 2024; Lü 2024).

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Declarations

Competing interests The authors declare no competing interests.

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