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Glass ornaments from southwestern Taiwan: new light on maritime glass exchange across Southeast, South and West Asia in the early-mid 1st millennium CE

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Abstract

A total of 146 glass samples from Daoye, Daoye South, and Wujiancuo in southwestern Taiwan were subjected to elemental analysis using LA-ICP-MS and SEM–EDS. These samples cover a time span from the first to the eighth century CE. The results provide evidence of the existence of multiple long-distance glass exchange networks that directly or indirectly connected Taiwan to Southeast Asia, South Asia, West Asia, and possibly the Mediterranean region. The predominance of the South Asian m-Na-Al glass sub-type 1 suggests that Taiwan mainly participated in the South China Sea maritime glass exchange network, while the identification of a newly recognised sub-type, m-Na-Al low Al low Ca, indicates the possibility of small-scale glass production workshops or a less controlled recipe for m-Na-Al glass production. Furthermore, this research reveals compelling evidence linking early v-Na-Ca glass found in Taiwan to origins in Mesopotamia or Sasanian territories, with the secondary production areas remain unclear. In addition, a potash glass and a Roman HIMT glass were also discovered. The chemical profiles of the potash glass do not align with those of early potash glass, while the HIMT glass can be attributed to the Roman Mediterranean. Taken together, these findings shed light on the intricate maritime exchange networks that operated over vast distances, spanning from the eastern part of the South China Sea to West Asia, covering over eight thousand kilometers. This study thus addresses a significant research gap regarding the maritime exchange of glass during the understudied period of the early to mid-1st millennium CE around the South China Sea and beyond.

Keywords Glass, Maritime exchange, Taiwan, Southeast Asia, Sasanian, LA-ICP-MS

Introduction

Glass played a crucial role as an indicator of inter-regional exchange activities in antiquity. Over the past few decades, the use of elemental analysis on glass artefacts from around the South China Sea region has revealed complex and multi-scalar exchange networks connecting continents through coastal and riverine traffics [1–8]. Current understanding indicates the presence of potash glass and mineral soda alumina (m-Na-Al) glass from fifth century BCE, the continuous dominance of m-Na-Al glass into the 1st millennium CE, and the appearance of plant ash glass (v-Na-Ca glass) principally from seventh-eighth century CE onwards. Potash glass

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was spread across the mainland Southeast Asia, as well as India and southern China. In Southeast Asia, potash glass appeared in Bon Don Ta Phet in west central Thailand as well as in several sites in peninsula Thailand and Myanmar but was less common in some regions such as Cambodia [2, 6, 9–11]. Additionally, at the Arikamedu site in South India, dating back to approximately the second century BCE, a considerable quantity of potash glass was also discovered [9]. The exact primary production areas of potash glass remain uncertain but multiple origins in this broad area are possible [9]. The primary production of m-Na-Al glass sub-type 1, the most widespread subtype in South and Southeast Asia in the 1st millennium CE, points to India and Sri Lanka [12]. V-Na-Ca glass post-dated the seventh-eighth century CE and is associated with West Asia, in particular the Islamic territories [8, 13, 14]. A few sites in South and Southeast Asia have also reported minor presence of 'early' v-Na-Ca glass, prior to seventh—eighth century CE [2, 15–18]. However, the origin of these 'early' v-Na-Ca glasses, mainly monochrome translucent dark blue and some are opaque blue, black, green or red glass beads, has tentatively been suggested as West Asia. This remains inconclusive due to the paucity of glass samples and research [14], although it has been suggested the likelihood of local glass beadmaking in Southeast Asia using glass cullet imported from Mesopotamia or Iran [17]. The temporal and spatial patterns of different compositional groups reveal the transition and expansion of interaction networks around the South China Sea and the neighbouring regions over more than a thousand years.

In past decades, despite the increase in glass studies around the South China Sea, our knowledge of glass exchange mainly derived from mainland Southeast Asia in 500 BCE—500 CE, and a few from Indonesia and Borneo in island Southeast Asia dated after late 1st millennium CE [2, 8, 19]. Glass exchange in the mid-late 1st millennium CE and in the eastern part of the South China Sea remain understudied. Recent scientific analyses on glass materials in Taiwan, however, have clearly revealed a strong connection to the South China Sea glass exchange network in the first half of 1st millennium CE as well as an extension of this network into the second half of the 1st millennium CE [20, 21]. Specifically, glass artefacts from Taiwan dating from the 1st millennium CE onwards exhibit a temporal pattern similar to that in Southeast Asia, with m-Na-Al glass being the principal presence over the 1st millennium CE, and the appearance of v-Na-Ca glass in a good quantity from mid-1st millennium CE [20–22]. This makes Taiwan an excellent contributor to fill in the lacunae in understanding glass exchange for the less studied period of mid-late 1st millennium from a chronological perspective, as well as for the eastern part of the South China Sea region from a regional perspective.

This article presents the latest elemental and microstructural analysis of glass artefacts from three Metal Age sites in southwestern Taiwan, namely Doaye (道爺), Daoye South (道爺南) and Wujiancuo (五間厝), dated to the first—eighth centuries CE. This is the first systematically analysed dataset of glass artefacts from southwestern Taiwan. Within Taiwan, most detailed research has been in southeastern and the southern end of the island [22, 23]. However, previous study has suggested potentially different glass exchange patterns in the southwestern region compared to southeast and northeast Taiwan, in particular the varied distribution of bead colours and styles [21]. Here, the results from southwestern Taiwan reveal not only the common presence of m-Na-Al glass but also early v-Na-Ca glass in a significant quantity before the contact with Islamic merchants in the South China Sea region during the late 1st millennium. This suggests the existence of long-distance interaction spheres from West Asia to Southeast Asia in early-mid 1st millennium CE. New sub-groups within m-Na-Al glass and v-Na-Ca glass are tentatively proposed, which confirms that southwestern Taiwan participated in a potentially different exchange network from other parts of Taiwan, and indicates the diversity of South China Sea glass exchange in both cross-regional and micro-regional scales. Additionally, the early v-Na-Ca glass reported here comprises glass beads as well as glass bangles/earrings, which is an artefact type that has not been found to have a v-Na-Ca glass composition in contemporary Southeast Asia.

Research sites and materials

The three sites under investigation (Daoye, Daoye South and Wujiancuo) are located in the present-day Tainan Science Park in southwestern Taiwan (Fig. 1). The Science Park's construction from 1990s onwards led to the discovery of more than sixty archaeological sites, spanning from the Neolithic Dabenkeng Culture (also known as Tapenkeng, circa 3000 BCE) to the early modern Siraya Culture (circa seventeenth century CE) [24]. Rescue excavations commenced in 1996 and continue to this day. Daoye and Wujiancuo were excavated by Professors Cheng-hwa Tsang and Kuang-ti Li between 1996 and 1999, while the Doaye South rescue excavations were carried out in 2004, 2006 and 2007 respectively, by the same excavation team.

All three study sites exhibit stratigraphy of the Metal Age Niaosong Culture (circa 2nd to fifteenth century CE). This culture is characterised by small to mid-sized plain red pottery jars, unique bird's head-shaped clay objects, iron daily tools or weapons and glass ornaments.

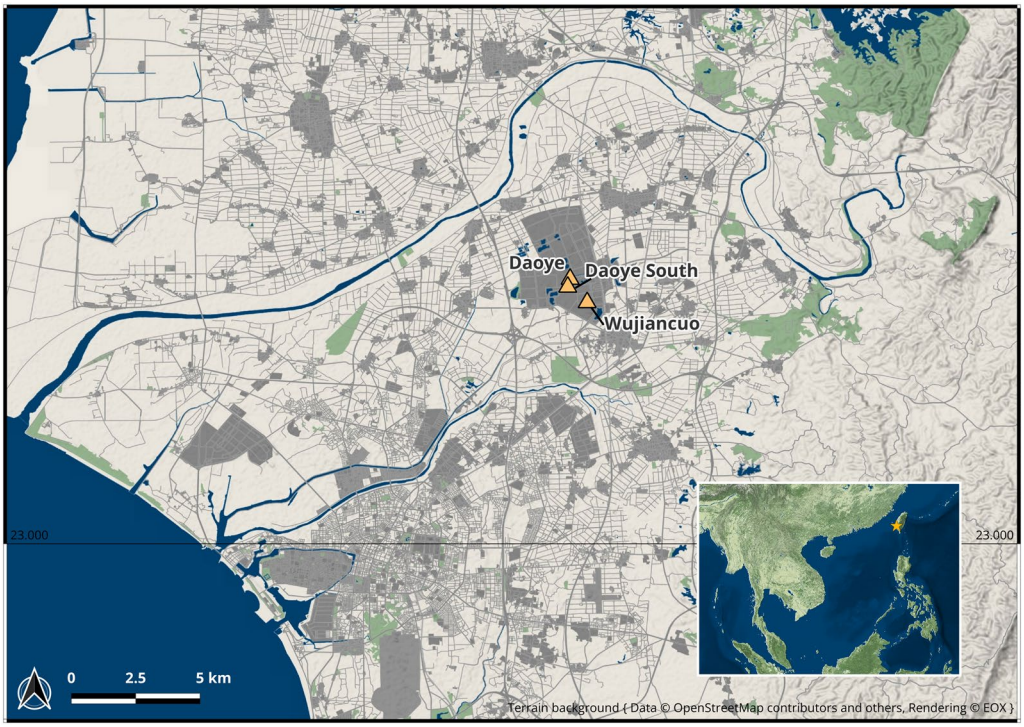


Fig. 1 Map showing the location of Daoye, Daoye South and Wujiancuo in Taiwan

Based on mainly the pottery assemblages and burial practices, the excavators have identified three sub-phases of the Niaosong Culture: the early Anzi Phase (2nd to sixth century CE), the middle Niaosong Phase (6th to tenth century CE) and the late Kanxi Phase (10th to fifteenth century CE) [24]. Daoye represents the early Anzi Phase, while Daoye South and Wujiancuo show cultural contexts of the middle Niaosong Phase. The radiocarbon dating suggests the occupation of Daoye in 1st—sixth centuries CE, Daoye South in 4th—eighth centuries CE and Wujiancuo in 5th—eighth centuries CE. All three sites exhibit settlement contexts with clustered inhumation burials which may be neighbouring the households. More details of the radiocarbon dating and the archaeological context variations are summarised in supplementary materials (Additional file 1).

The glass assemblage consists of glass beads and bangles/earrings. At Daoye, a total of 62 glass beads and 8 bangles or earrings were discovered, while a significantly larger amount of glass beads, over 1600, and 2 broken pieces of bangles, which may belong to the same item, were excavated at Daoye South (Table 1). A limited quantity of glass artefacts were unearthed at Wujiancuo, comprising less than 40 beads and no bangles or earrings.

The glass beads are all monochromatic, with an oblate or tubular shape. Most glass beads are drawn, while a few are wound beads. A preponderance of blue and green beads is evident at all three sites, while red, orange and yellow beads are less prevalent, with a few beads of dark blue, black or aqua colours (Table 1). Only green, blue or dark blue bangles or earrings were found, with a circular, semi-circular or house-shaped cross-section (Fig. 2).

At Daoye, around half of the glass beads and four glass bangles/earrings were retrieved from burial contexts. Glass beads from non-burial context were mainly from ash pits or contexts which are yet to be determined. A thorough analysis of the styles and colour distribution did not reveal any distinct differences between burial or non-burial contexts. The beads and bangles/earrings were found in mortuary contexts with six individuals, with a quantity ranging from one to less than 20. No burials contain both glass beads and bangles/earrings. At Daoye South, the glass bangles and over 85% of the glass beads were grave goods, and the rest of beads were from ash pits which may be associated with habitation contexts. Sixty-one individuals were buried with glass beads, and variations in bead quantities and colours can be observed. Less than five individuals were buried with close to 100 pieces of glass beads, around 10 burials had fewer than 50 beads, and most are buried with less than 20 glass beads. Blue beads are the most common grave goods, while two burials are particularly rich in red, orange or yellow beads. Similar to Doaye, the glass bangles at Daoye South were discovered in a burial without

Table 1 Colour distribution of glass artefacts

Colour	Sample condition	DY		DY-SUM		DYS		DYS-UM		WJC		WJC-SUM	
		Bead	Bangle, earring	Bead	Bangle, earring	Bead	Bangle, earring	Bead	Bangle, earring	Bead	Bangle, earring	Bead	Bangle, earring
Red	Intact	4	0	**4**	**0**	77	0	**89**	**0**	1	0	**1**	**0**
	Fragment	0	0			12	0			0	0		
Orange	Intact	0	0	**0**	**0**	57	0	**57**	**0**	0	0	**0**	**0**
	Fragment	0	0			0	0			0	0		
Yellow	Intact	5	0	**7**	**0**	13	0	**17**	**0**	1	0	**1**	**0**
	Fragment	2	0			4	0			0	0		
Green	Intact	21	0	**23**	**4**	128	0	**157**	**0**	7	0	**8**	**0**
	Fragment	2	4			29	0			1	0		
Blue	Intact	24	0	**27**	**2**	933	0	**1312**	**2**	23	0	**25**	**0**
	Fragment	3	2			379	2			2	0		
Dark blue	Intact	0	0	**0**	**2**	3	0	**3**	**0**	3	0	**4**	**0**
	Fragment	0	2			0	0			1	0		
Black	Intact	1	0	**1**	**0**	3	0	**3**	**0**	0	0	**0**	**0**
	Fragment	0	0			0	0			0	0		
Aqua	Intact	0	0	**0**	**0**	0	0	**1**	**0**	0	0	**0**	**0**
	Fragment	0	0			1	0			0	0		
Total	Intact	55	0	**62**	**8**	1214	0	**1639**	**2**	35	0	**39**	**0**
	Fragment	7	8			429	2			4	0		

(Unit: piece) (distorted-shaped objects at Daoye are not counted here)

any glass beads. At Wujiancuo, glass beads were primarily recovered from ash pits. There are around 10 beads reported from three burials.

Analytical methods

Sampling

A total of 146 samples were selected for analysis, including 38 from Daoye, 102 from Daoye South and 6 from Wujiancuo (Table 2). The samples were selected to represent a wide range of colours and types of glass ornaments from both burial and non-burial contexts. Non-destructive analysis using LA-ICP-MS was performed on all 146 samples, while 27 samples underwent additional destructive analysis using SEM–EDS. Detailed information of the samples can be found in Additional file 2: Table S1. Notably, after a closer observation, a specific type of light green beads from Daoye South were considered as a single group in Table 2 but not in the original catalogue (Table 1), as they exhibit distinct morphological, elemental and microstructural features from other green beads which may suggest possible differences in their provenances (see below).

SEM–EDS

The microstructure of the glass samples was investigated using a field emission Scanning Electron Microscope equipped with Energy Dispersive X-ray Spectrometer (SEM–EDS, JEOL JSM-7100F with Oxford EDS). Such investigations have the potential to reveal crystals or relics associated with the raw materials (such as sand or colourant) or the production processes [25]. The analyses were carried out at the Institute of Earth Sciences, Academia Sinica, Taiwan. A small piece of the glass sample was cut and then mounted in epoxy resin, then ground and polished by diamond suspension down to 1 μm. The polished samples were subsequently carbon coated and analysed using an accelerating voltage of 15 kV, a beam current of 0.1 nA and the working distance of 10 mm. The beam current was monitored using a probe current detector and chemical composition of each analysis was corrected by the oxide ZAF.

LA-ICP-MS

Quantitative bulk chemical analyses down to trace elemental level were carried out using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The purpose is to obtain full elemental data to assess the compositional groups as well as any elemental patterns associated with regional provenances. LA-ICP-MS is a quasi-non-destructive technique that leaves no visible damage at the surface of the object. It ablates a crater with a diameter of 100 microns or less (equivalent to the diameter of a human hair) using a laser beam.

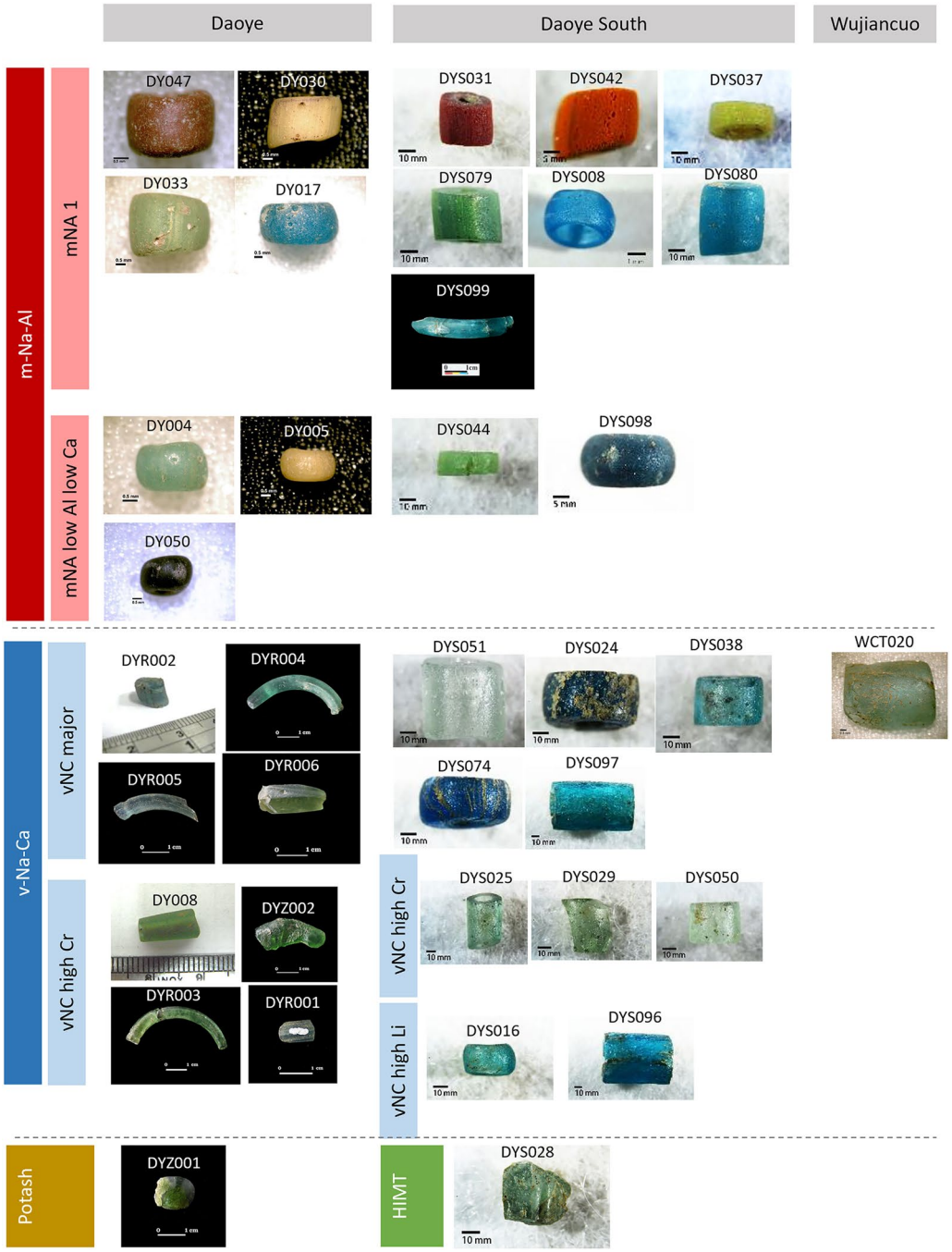


Fig. 2 Image of glass objects from Daoye, Daoye South and Wujiancuo, together with their associated chemical groups

The analysis was undertaken at the Elemental Analysis Facility at the Field Museum of Natural History in Chicago in the United States, using a Thermo ICAP Q Inductively Coupled Plasma Mass Spectrometer (ICP-MS) connected to a New Wave UP213 laser for sample introduction. The ICP-MS parameters were optimised to ensure a stable signal with maximum intensity across the full range of element masses, and to minimise oxides and double-ionised species formation (with XO^+/X^+ and X^{++}/X^+ <1 to 2%). This was achieved by adjusting the argon flows, RF power, the torch position, the lenses, the mirror and detector voltages using an auto-optimisation procedure. Helium was used as a gas carrier in the laser for better sensitivity.

Table 2 An overview of selected samples from each site, and their artefact types, contexts, colour distribution and compositional groups

		DY	DYS	WJC	Total
Total sample number		**38**	**102**	**6**	**146**
SEM–EDS analysis		8	15	4	**27**
Context distribution					
Non-burial		22	7	6	**35**
Burial		16	95	0	**111**
Artefact type, colour and compositional group					
m-Na-Al 1					
Bead	Red	3	7	0	**10**
	Orange	0	3	0	**3**
	Yellow	3	3	0	**6**
	Green	5	11	0	**16**
	Blue	15	43	5	**63**
Bangle/earrings	Blue	0	2	0	**2**
SUM (m-Na-Al 1)		**26**	**69**	**5**	**100**
m-Na-Al low Al low Ca					
Beads	Yellow	1	0	0	**1**
	Green	1	5	0	**6**
	Dark blue	0	1	0	**1**
	Black	1	0	0	**1**
SUM (m-Na-Al low Al low Ca)		**3**	**6**	**0**	**9**
v-Na-Ca major					
Bead	Light green	0	1	0	**1**
	Blue	0	8	1	**9**
	Dark blue	0	4	0	**4**
Bangle/earrings	Green	1	0	0	**1**
	Blue	2	0	0	**2**
	Dark blue	1	0	0	**1**
SUM (v-Na-Ca)		**4**	**14**	**1**	**19**
v-Na-Ca high Cr					
Bead	Green	1	0	0	**1**
	Light Green	0	7	0	**7**
Bangle/earrings	Green	1	0	0	**1**
	Dark blue	1	0	0	**1**
Distorted-shaped	Blue	1	0	0	**1**
SUM (v-Na-Ca high Cr)		**4**	**7**	**0**	**11**
v-Na-Ca high Li					
Bead	Blue	0	6	0	**6**
SUM (v-Na-Ca high Li)		**0**	**6**	**0**	**6**
Potash					
Unknown artefact	Green	1	0	0	**1**
SUM (potash)		**1**	**0**	**0**	**1**
HIMT (Roman)					
Bead	Green	**0**	**1**	**0**	**1**
SUM (HIMT)		**0**	**1**	**0**	**1**

DY Daoye, *DYS* Daoye South, *WJC* Wujiancuo

Single point analysis mode was used with a laser beam diameter of 80 μm, operating at 70% of the laser energy (0.2 mJ) and at a pulse frequency of 15 Hz. A pre-ablation time of 20s was set to eliminate the transient part of the signal and ensure that any possible surface contamination or corrosion did not affect the results of the analysis. For each glass sample, the average of four measurements corrected from the blank was used to calculate concentrations.

^{29}Si was used for internal standardisation. For major elements, including silica, their concentrations are determined by assuming that their sum in weight percent equals 100% [26]. To measure major, minor, and trace elements, two different sets of external standards were utilised. The first set consists of standard reference materials (SRM) produced by the National Institute for Standards and Technology, namely SRM610 and SRM612. Both are soda-lime-silica glasses with trace element concentrations ranging from 500 ppm (SRM610) to 50 ppm (SRM612), with certified values available for a limited number of elements. For other elements, concentrations from Pearce et al. [27] are used. The second set of standards was manufactured by Corning Museum of Glass, which includes Glass B and D that match the compositions of ancient glass [28]. Detection limits for most elements range from 10 ppb to 1 ppm, and accuracy varies from 5 to 10% depending on the element and its concentration. For more details on the performance of this technique, please refer to Dussubieux's recent work [29].

Results

Four compositional groups were identified in this research, namely mineral soda alumina glass (m-Na-Al), soda plant ash glass (v-Na-Ca), potash glass and Roman High Manganese, Iron and Titanium (HIMT) glass (Table 2, Fig. 3). The comprehensive results of elemental analysis can be found in the Additional file 2: Table S1. The m-Na-Al glass group (n = 109) constitutes more than three quarters of the analysed samples at each site and mainly belongs to the sub-type 1. However, some samples exhibit varied minor and trace elemental pattern and are tentatively categorised as m-Na-Al low Al low Ca subtype (see below). V-Na-Ca glass (n = 35) is the second most prevalent compositional group. Three sub-groups of v-Na-Ca glass (v-Na-Ca major, v-Na-Ca high Cr, v-Na-Ca high Li) are tentatively suggested in this research. Only 1 potash glass sample and surprisingly 1 HIMT glass were identified.

At the Daoye site, nearly all glass beads are composed of m-Na-Al glass, while all bangles/earrings are made of v-Na-Ca glass. At Daoye South, the proportion of v-Na-Ca glass increases, although m-Na-Al glass remains dominant. It is worth noting that the only two bangle

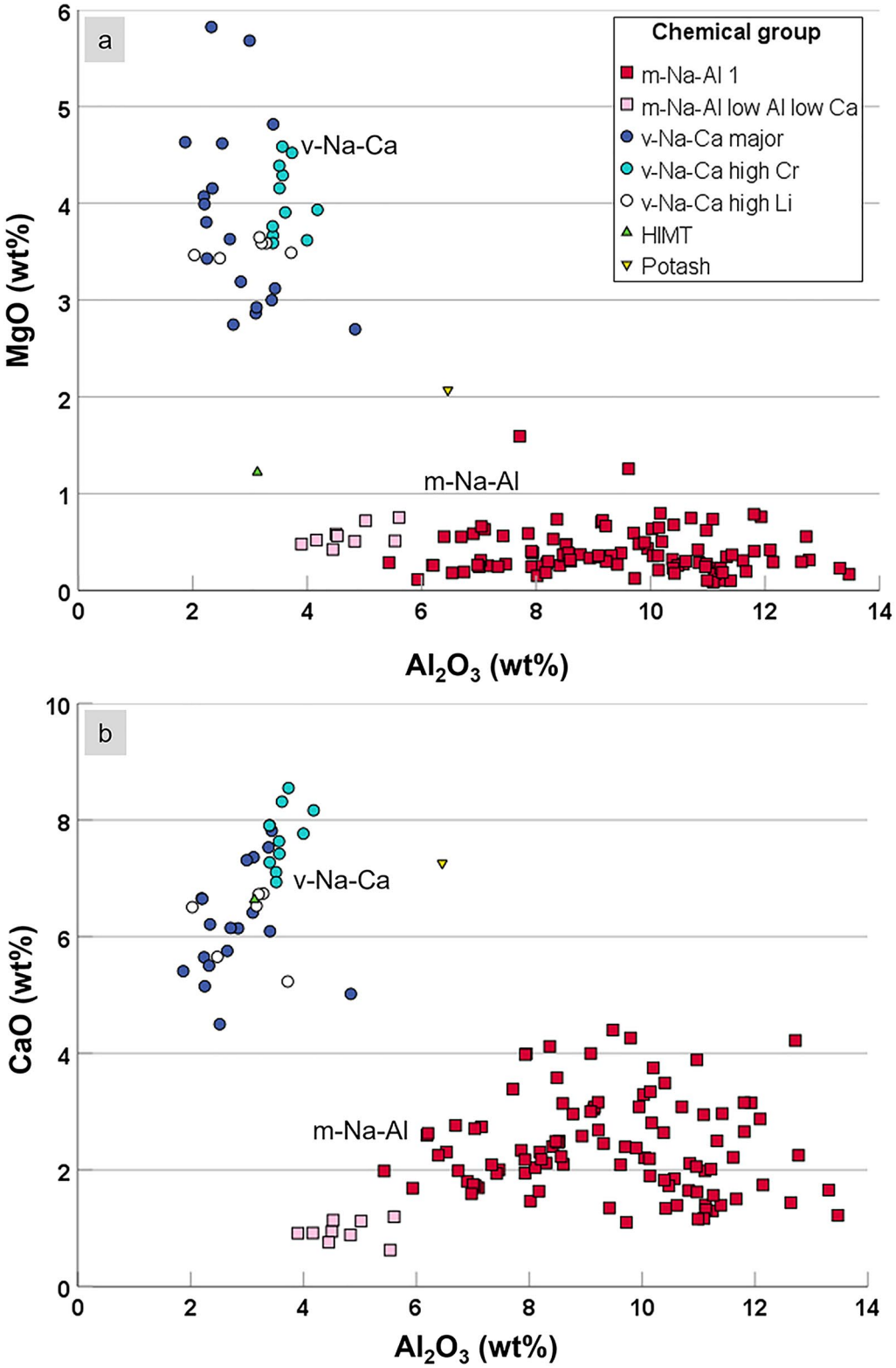


Fig. 3 Bivariate plots of (a) Al_2O_3-MgO and (b) Al_2O_3-CaO showing the compositional groups of glass artefacts from Daoye, Daoye South and Wujiancuo

fragments from Daoye South have a m-Na-Al glass composition, which is different from the compositional group of the bangles/earrings at the Daoye site. Glass beads composed of m-Na-Al glass or v-Na-Ca glass are frequently discovered in the same burial at Daoye South, indicating that the two compositional groups circulated in the exchange network concurrently. A small number of beads from Wujiancuo were also analysed, and these samples include five m-Na-Al glass beads and one v-Na-Ca glass beads.

There is noticeable correlation between compositional groups and colour distribution. Glass beads of a m-Na-Al glass composition exhibit an opaque red, orange, yellow, green, blue, dark blue or black colour, while v-Na-Ca glass beads are translucent light green, green, blue, aqua or opaque dark blue. Regarding bangles/earrings, the v-Na-Ca glass objects from Daoye have a translucent blue or green colour with a circular, semi-circular or house-shaped cross-section, while the m-Na-Al glass bangle from Daoye South is opaque blue, with a house-shaped cross-section. The potash glass has a green colour, and the HIMT glass is also green, which is typical of Roman HIMT glass. The results of each compositional group are elaborated below.

Mineral soda alumina glass (m-Na-Al 1 and m-Na-Al low Al low Ca)

The m-Na-Al glass found at Daoye, Doaye South and Wujiancuo contains 5–13 wt% Al_2O_3, 12–22 wt% Na_2O and less than 1.5 wt% MgO. This suggests a production tradition using mineral soda as a flux and silica sand enriched in aluminosilicate minerals such as feldspar [12, 30]. SEM–EDS analysis commonly reveals incompletely melted zircon and sodium-rich feldspar from raw materials. Further comparison using Mg, Ca, Zr, Ba, Sr and U, as suggested by Dussubieux and colleagues [12], indicates that most m-Na-Al glass in this research belong to subtype 1, characterised by its high barium and low uranium contents (Fig. 4). Optical microscope observation suggests the use of drawn method of beadmaking.

Nine samples (DY004, DY005, DY050, DYS018, DYS019, DYS044, DYS075, DYS045, DYS098) from Daoye and Daoye South are not fully consistent with the m-Na-Al sub-type 1 (Fig. 4). All are drawn glass beads. A closer examination reveals that, in comparison to m-Na-Al sub-type 1, these samples have low Al_2O_3 (4–6 wt%) and low CaO (< 1.5 wt%) contents (hereafter m-Na-Al low Al low Ca), and are mostly opaque green beads, with an additional yellow bead, a dark blue bead and a black bead. Across the South and Southeast Asia, there are

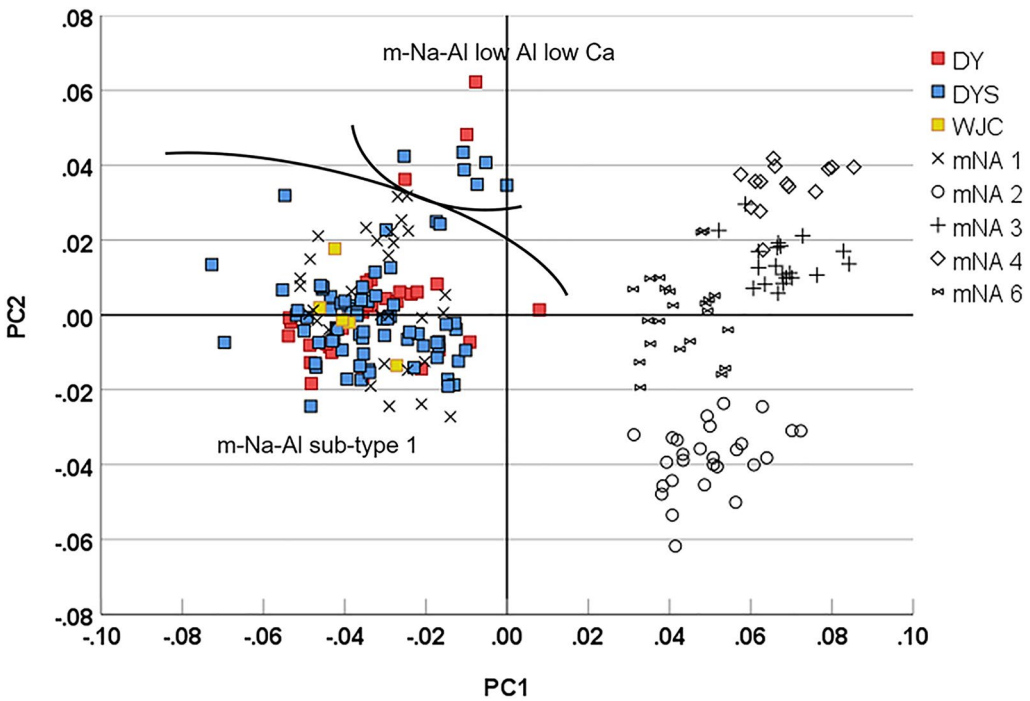


Fig. 4 Principal component analysis using Mg, Ca, Zr, Ba, Sr and U suggests most samples belong to m-Na-Al sub-type 1, while a few belong to a new type m-Na-Al low Al low Ca. (The comparative m-Na-Al 1 glass samples are unpublished data from Sri Lanka and South India, the m-Na-Al 2 glass samples are beads from Chaul, Maharashtra, India [32], the m-Na-Al 3 glass samples are beads from Kopia, Uttar Pradesh, India [33], the m-Na-Al 4 glass samples are glass vessel fragments from Sumatra [34] and the m-Na-Al 6 samples are beads from the Juani School site on the island of Mafia in Tanzania [35])

two types of high alumina soda glass that contain low Al_2O_3 and CaO, namely m-Na-Ca-Al glass and Arika glass. PCA analysis using Na, Al, Rb, Zr, La, Hf, and Th, as suggested by Dussubieux and Gratuze [31] indicates that the m-Na-Al low Al low Ca glass in southwestern Taiwan does not fit in the m-Na-Ca-Al glass (Fig. 5). It is noted that the CaO contents in the m-Na-Al low Al low Ca glass (< 1.5 wt%) are lower than that in m-Na-Ca-Al glass and Arika glass (1.5–6 wt%), and the Zr contents are high in m-Na-Al low Al low Ca glass (> 700 ppm) but much lower in m-Na-Ca-Al and Arika glass (< 300 ppm). The m-Na-Al low Al low Ca glass thus is likely to be a new sub-type of high alumina soda glass circulated during early to mid-1st millennia around the South China Sea. A comparison between the m-Na-Al sub-type 1 and m-Na-Al low Al low Ca samples from Daoye and Daoye South further indicates that the m-Na-Al low Al low Ca glass contains, on average, elevated levels of B (close to 150 ppm), Li (> 15 ppm), Cs (close to 1 ppm), Cr (> 60 ppm), but slightly low Sr (< 100 ppm). This suggests the use of a slightly different sand source in the low Al low Ca glass samples, which contains varied trace elements compared to the major m-Na-Al sub-type 1 glass.

At Daoye, Daoye South and Wujiancuo, the m-Na-Al sub-type 1 glass exhibits a variety of colours including red, orange, yellow, green and blue. Copper oxide is responsible for the red, orange and blue colours in these glass samples, with cuprite or metallic copper giving rise to the red and orange colour in a reduction atmosphere, while cupric copper, as ionic copper dissolved in the glass network, is responsible for the blue colour in an oxidised atmosphere. The CuO content in the red and blue glass is less than 2 wt%, whereas in the orange glass it is more than 4 wt%. The red and orange glass also contain slightly more Fe_2O_3 (> 2 wt%) than the blue glass (< 2 wt%), suggesting an additional amount of Fe-containing ingredient may have been introduced to facilitate the reduction of cuprite or metallic copper [12, 25]. Lead stannate ($Pb(Sn,Si)O_3$) imparts the yellow colour in the glass, with PbO ranging between 3 and 5 wt% and SnO_2 varying between 0.2 and 1 wt%. The green glass is coloured by both yellow and blue colourants, i.e. lead stannate and cupric copper, and the levels of CuO, PbO and SnO_2 in the green glass are generally the same as those in the blue and yellow glass. SEM–EDS analysis of yellow and green glass revealed two types of microstructures: small lead stannate crystals clustered with large newly formed nepheline in the first case and lead stannate crystals agglomerate as a single component in the second case. These two microstructures suggest that different or less standardised production processes may have been used to prepare the yellow colouring agents [25].

In the m-Na-Al low Al low Ca glass, the colourants for yellow and green glass, as well as the levels of CuO, PbO and SnO_2, are similar to those in the m-Na-Al 1 subgroup. Notably, lower Ba (< 300 ppm) can be observed in the yellow and green m-Na-Al low Al low Ca glass, but not the dark blue and black samples, than in the

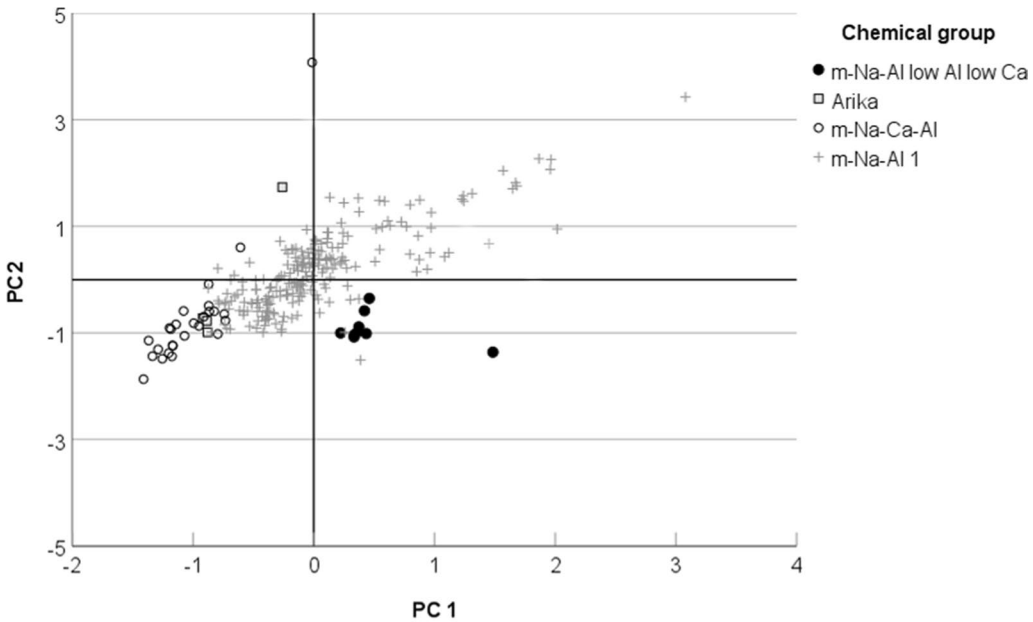


Fig. 5 Principal component analysis using Na, Al, Rb, Zr, La Hf and Th showing the differences between m-Na-Al low Al low Ca, m-Na-Ca-Al, Arika and m-Na-Al 1 sub-groups. (The comparative data are from Phum Snay, Prei Khmeng, Prohear, Lovea, Sophy in Cambodia [15, 36] and Aw Gyi in Myanmar [7])

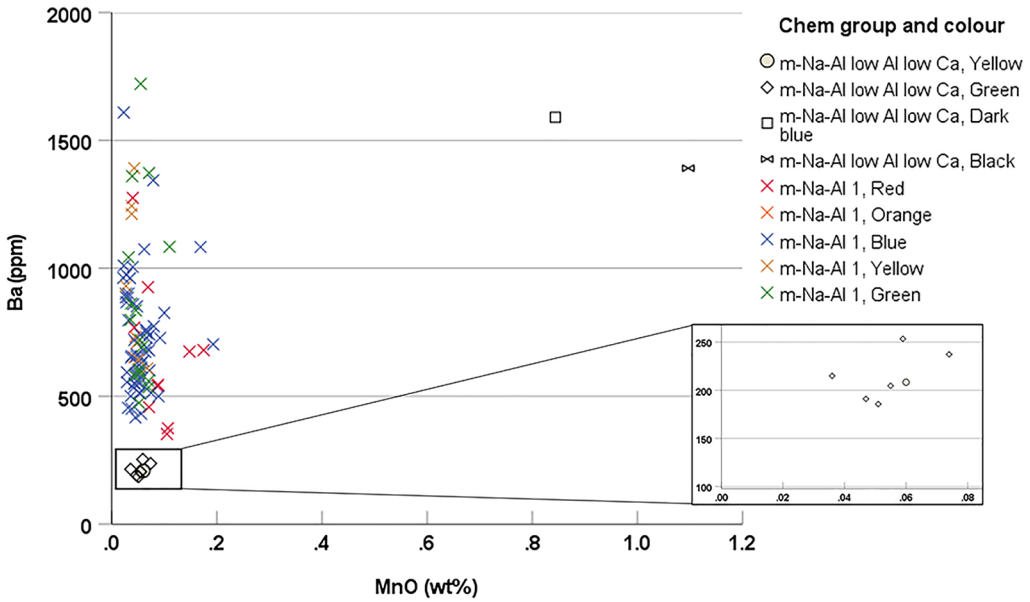


Fig. 6 Bivariate plot of MnO-Ba, showing the elevated level of Ba in the manganese- and copper-coloured dark blue and black glass samples of a m-Na-Al low Al low Ca glass composition

m-Na-Al 1 glass (Fig. 6). The colour of dark blue glass (DYS098) and black glass (DY050) with an m-Na-Al low Al low Ca glass composition are attributed to a mixing effect of copper and manganese, with an elevated concentration of CuO close to 1.5 wt% and MnO more than 0.8 wt%. The cobalt content at low level (~ 20 ppm) suggests that cobalt has almost no effect on the strong colour hue of DY050 and DYS098. Here, the high barium content in DY050 and DYS098 may be associated with the introduction of manganese colourant from psilomelane $(Ba,H_2O)_2Mn_5O_{10}$), which is a manganese-based mineral with a significant proportion of barium that can be found in India [37–39].

Plant ash glass (v-Na-Ca major, v-Na-Ca high Cr, v-Na-Ca high Li)

V-Na-Ca (soda plant ash) glass in Daoye, Daoye South and Wujiancuo contains Na_2O between 12 and 20 wt%, K_2O in 1.5–4 wt%, MgO in 2.5–6 wt% and CaO ranging from 4.5 to 8.5 wt%. The high concentration of soda and magnesia suggests the use of a fluxing agent of ashes obtained from salt resistant, halophytic plants. At Daoye, there are six green or blue bangles/earrings, one green object with a distorted shape and one green glass bead made of v-Na-Ca glass. At Daoye South and Wujiancuo, all v-Na-Ca glass samples are monochrome glass beads in a translucent blue, dark blue, aqua, green or light green colour.

V-Na-Ca glass first appeared in the Late Bronze Age Egypt, the Near East and Mesopotamia in around the 3rd millennium BCE. In Egypt and the Near East, the Roman soda natron glass became dominant from the eighth century BCE to eighth century CE [40–43], while in Mesopotamia the v-Na-Ca glass continued to be the major compositional group throughout the Persian, Parthian, Sasanian and Islamic periods from the sixth century BCE onwards [41, 44–49]. In the South China Sea, most v-Na-Ca glass objects were found in archaeological sites dating after the seventh—eighth century CE, with the primary production associated with the Islamic world in West Asia [8, 14, 34, 50]. Dussubieux and Allen [50] have identified three sub-types of the 'late' v-Na-Ca glass, mainly based on materials dated in ninth—eleventh centuries CE, in Southeast Asia. The sub-types derived from these late v-Na-Ca glass samples may not necessarily apply to the early v-Na-Ca glass samples predating the seventh—eighth centuries CE in this research.

In recent decades, research has started to show the existence of regional and temporal compositional groups of v-Na-Ca glass, based on the elemental patterns, across the Mediterranean, the Near East and Mesopotamia, where there was evidence for primary production [41, 43, 51, 52]. Phelps proposed a subdivision using MgO/CaO ratio and the content of Al_2O_3 to distinguish between chemical groups in Eastern Mediterranean and Mesopotamia [52]. By applying the criteria to v-Na-Ca glass samples from southwestern

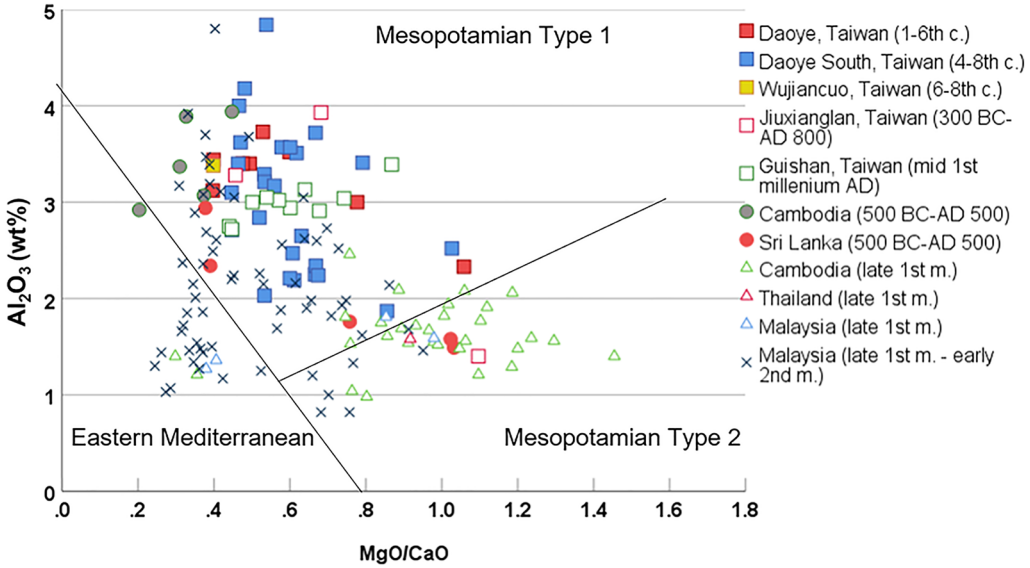


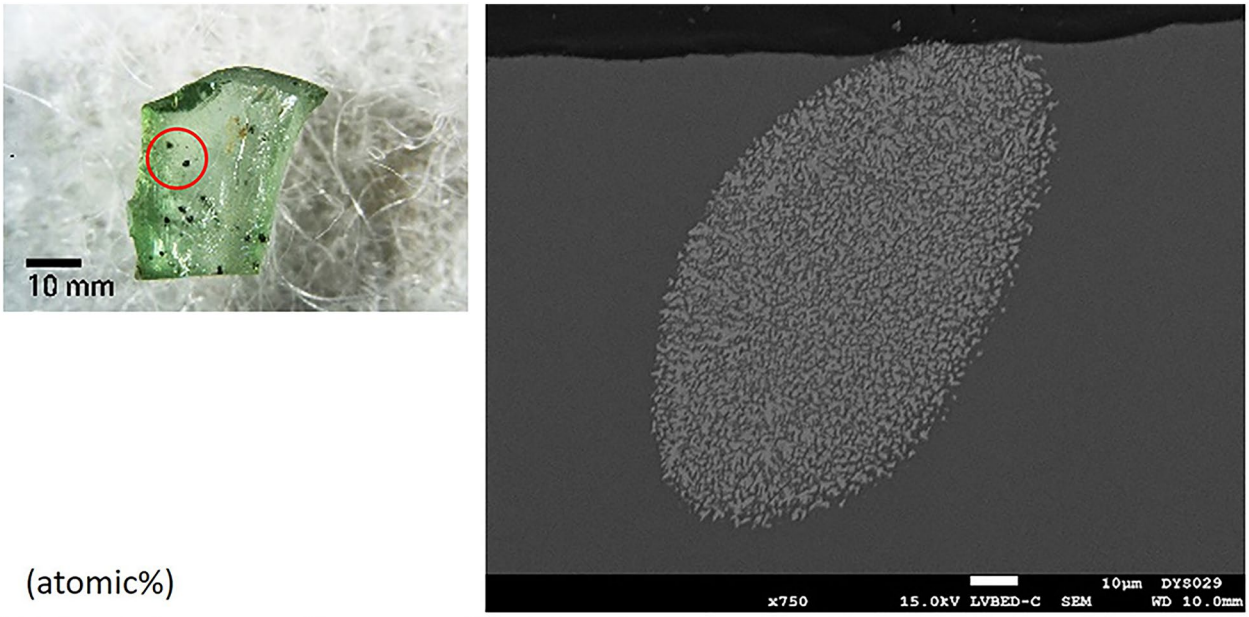
Fig. 7 Bivariate plot of MgO/CaO to Al_2O_3 showing the v-Na-Ca glass from southwestern Taiwan fits in the Mesopotamian Type 1 as suggested by Phelps [52]

Taiwan, it can be clearly seen that they fit into the Mesopotamian Type 1 sub-group (Fig. 7). The Mesopotamian Type 1 contains the Sasanian glass from Veh Ardašīr in Iraq dating to third—seventh century CE [47, 48] and Islamic glass from Nishapur and Samarra in Iraq, both dating back to ninth—tenth century CE [19, 53]. These findings suggest that the v-Na-Ca glass in southwestern Taiwan is likely to have originated in Mesopotamia. This conclusion can be further supported by the absence of soda plant ash glass production in the Eastern Mediterranean area during the period of the dating of glass ornaments in this research (first—eighth century CE) [40–42, 47, 48].

Further evidence supporting the Mesopotamian origin of the v-Na-Ca glass can be found in the compositional profiles of several elements and the microstructural analysis using SEM–EDS. Compared to the v-Na-Ca glass from the Near East and Egypt, it has been suggested that the Mesopotamian glass generally contains greater MgO (> 3.5 wt%), a higher Cr/La ratio (> 5) and Li/Na_2O ratio (with lithium more than 10 ppm) but lower amounts of P_2O_5 (< 0.4 wt%) and TiO_2 (< 0.3 wt%) [41, 43]. Additionally, a high MnO content (> 0.5 wt%) is frequently observed in v-Na-Ca glass dating back to the subsequent Islamic period in the Middle East [49, 54, 55], which suggests the intentional addition of manganese as a colourant or decolouriser. However, the elevated level of MnO is seldom reported in v-Na-Ca glass prior to the Islamic period in Mesopotamia. An examination on the v-Na-Ca glass from southwestern Taiwan indicates the broad similarity to the early Mesopotamian counterparts, with MgO content greater than 3 wt%, P_2O_5 less than 0.4 wt%, Ti content below 2000 ppm (equivalent to TiO_2 of 0.33 wt%), Cr/La generally greater than 5 and Li/Na_2O higher than 0.5. The MnO contents lower than 0.3 wt%, together with the radiocarbon dating of the research site, further suggests that the southwestern Taiwan samples belong to the 'early' v-Na-Ca glass associated with the Sasanian primary glass production.

An increasing level of Cr is routinely observed in the v-Na-Ca glass. The elevated level of Cr and the greater Cr/La ratio in v-Na-Ca glass is considered to be a robust indicator of Mesopotamian glass, as the Tigris and Euphrates basins contain chromite-bearing sands that originate from the deposits in mountainous headwaters [43]. Here, magnesiochromite ($MgCr_2O_4$) is observed in a light green glass bead from Daoye South (DYS029) and an aqua bead from Wujiancuo (WJC020) (Fig. 8), which explains the high Cr contents in the v-Na-Ca glass as well as reinforces the likelihood of a Mesopotamian origin of the v-Na-Ca glass in southwestern Taiwan.

Based on the Cr/La and Li/Na_2O ratio, three sub-groups can be identified in the samples from Daoye, Daoye South and Wujiancuo (Fig. 11a). Six samples from Daoye South (DYS011, DYS015, DYS016, DYS066, DYS069, DYS096) exhibit particularly high Li/Na_2O (> 1.5) but relatively low Cr/La ratio (< 1.5) (hereafter v-Na-Ca high Li). The low Cr/La ratio in the v-Na-Ca high Li sub-group is due to its extremely low Cr content below 20 ppm. All samples in this sub-group are translucent blue glass beads. In some cases, the marks on bead surfaces clearly suggest a drawn method, but in most



(atomic%)

Na	Mg	Si	K	Ca	Cr	Fe	O
1.9	10.1	5.4	0.4	0.8	22.1	1.7	57.6

Fig. 8 SEM–EDS analysis showing the black particles within the light green glass bead are magnesiochromite (DYS029)

cases, it is hard to confirm the beadmaking methods as drawn or wound.

The second sub-group, v-Na-Ca high Cr, is designated for its particularly high Cr/La ratio (> 30) and Cr content (> 150 ppm). Samples in this sub-group are all translucent green glass, except for 1 dark blue glass bangle fragment from Doaye. The translucent green glass includes 7 light green drawn glass beads (DYS021, DYS025, DYS029, DYS050, DYS052, DYS053, DYS054) from Daoye South, in which magnesiochromite minerals were observed in one sample, as well as 1 glass bead, 1 earring and 1 distorted object from Daoye. The only green glass bead with a v-Na-Ca high Cr composition at Daoye is larger in size than other glass beads in this research, with a long tubular shape tapered towards one side (Fig. 2). The lack of clear manufacturing marks on this green bead surface makes it hard to evaluate its beadmaking method.

The remaining samples are designated as the major v-Na-Ca glass group (hereafter v-Na-Ca major), which has moderate Cr/La and Li/Na_2O ratios. Glass beads in the v-Na-Ca major group are drawn or wound beads.

Differences between Al_2O_3 and Ce can be observed in the three sub-groups. The v-Na-Ca high Li has higher Ce (> 15 ppm) and thus a greater Al_2O_3-Ce slope than the v-Na-Ca major and v-Na-Ca high Cr sub-groups (Fig. 9b). More Al_2O_3 can be observed in the v-Na-Ca high Cr samples. Ti and Zr levels are also higher in the v-Na-Ca high Cr samples compared to the v-Na-Ca high Li samples. These impurities, including alumina, cerium, chromium, titanium and zirconium, are related to the silica sand, suggesting the use of various sand sources, particularly in the v-Na-Ca high Li sub-group.

Regarding colourants, the blue glass is coloured by cupric copper, with CuO levels ranging between 0.5 and 2 wt%. Two copper-containing ingredients may have been used in the v-Na-Ca major and v-Na-Ca high Li sub-groups, respectively. As shown in Fig. 10a and b, linear correlation between CuO, SnO_2 and PbO is clearly observed in the majority of the v-Na-Ca major group but not in the v-Na-Ca high Li samples. The correlation between CuO and SnO_2 suggests bronze (in an oxidised form) may have been the colouring agent in the v-Na-Ca major group, and the distinct PbO content likely indicates the use of a leaded bronze. In contrast, tin-free copper may be the main ingredient in the v-Na-Ca high Li samples. Trace elements in association with copper also shows differences between the two sub-groups. The v-Na-Ca major group generally exhibits higher levels of Ni, Zn, Ag and Sb than the v-Na-Ca high Li group (Fig. 10c and d). This suggests that fewer impurities were introduced from the copper colourant into the v-Na-Ca high Li glass.

The dark blue colour is attributed to cobalt. Higher Co contents (350–450 ppm) are observed in the four samples from Daoye. The two dark blue glasses from Doaye South have Co below 150 ppm. No distinct

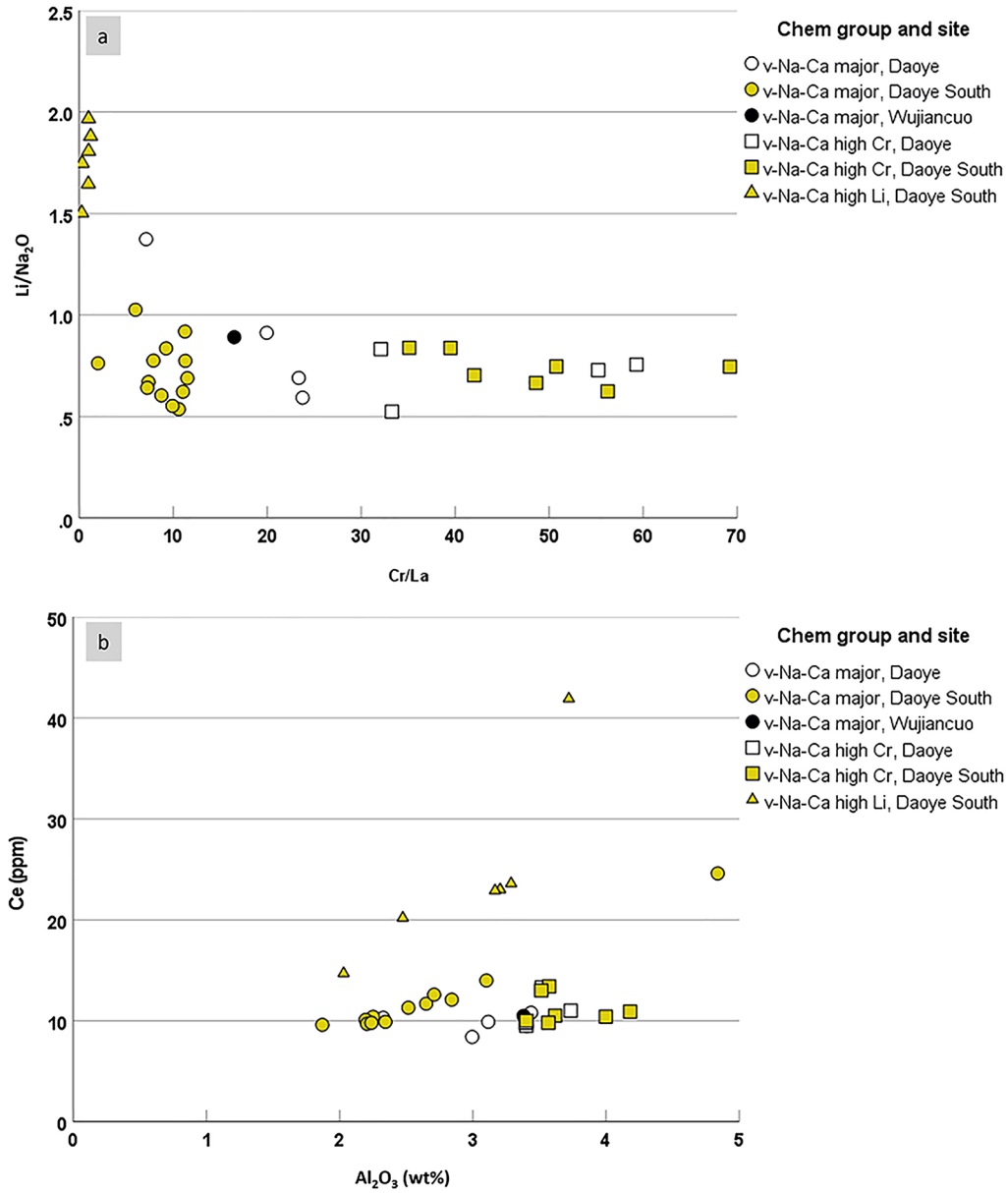


Fig. 9 Bivariate plots of (a) Cr/la ratio to Li/Na_2O ratio showing the sub-groups of v-Na-Ca glass, and (b) Al_2O_3-Ce showing different correlation in each sub-group

differences are found in dark blue glass between the v-Na-Ca major and v-Na-Ca high Cr sub-groups. While cobalt source used for Mesopotamian glass may contain high nickel [56], considerably low nickel (< 50 ppm) is observed in the dark blue samples from southwestern Taiwan. Other cobalt-related elements are also relatively low, with MnO below 0.35 wt%, Ba below 400 ppm, Zn below 50 ppm, As below 4.5 ppm. It is noteworthy that later v-Na-Ca glass around the South China Sea coloured with cobalt have a Co-As or Co-Zn association [8], while this is not observed in the early v-Na-Ca glasses in this research.

The green and light green samples are coloured by ferrous iron (Fe^{2+}). All samples exhibit Fe_2O_3 contents below 1.7 wt% and CuO in negligible amounts, suggesting that the iron impurities from the silica sand naturally coloured these samples. No differences were observed for the recipe of colouring agent for the green or light green glass between v-Na-Ca major and v-Na-Ca high Cr groups.

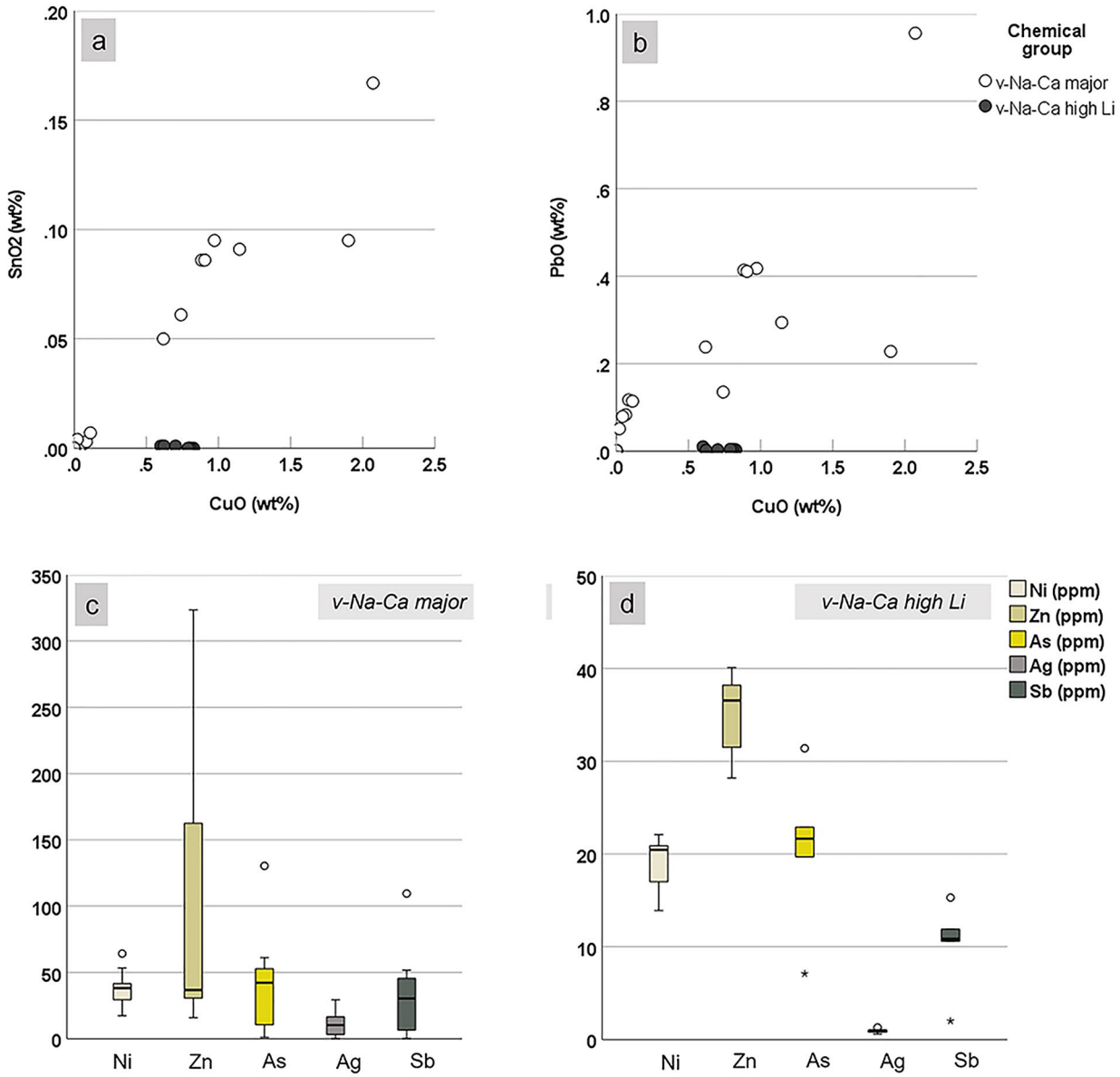


Fig. 10 Bivariate plot of (**a**) CuO-SnO_2 and (**b**) CuO-PbO showing the use of different copper-containing ingredients as colourants in the blue glass in the v-Na-Ca major and v-Na-Ca high Li sub-groups. (**c**) and (**d**): Lower concentration of the impurities related to the copper colourants can also be observed in the v-Na-Ca high Li sub-group than the v-Na-Ca major sub-group

HIMT glass

A translucent green bead fragment (DYS028) has been found to have a HIMT glass composition. HIMT glass is a Roman natron-type soda-lime-silica glass with particularly high iron, manganese and titanium contents [57]. It is a widespread Roman glass composition across the Mediterranean and central and northern Europe during fourth—seventh century CE, but to a lesser extent in the Near East [58–61]. Freestone et al. [59] suggest an Egyptian origin for the primary glass production. The HIMT glass from Daoye South contains Na_2O 19 wt%, CaO 6.6 wt%, MgO 1.2 wt%, Fe_2O_3 1.72 wt%, MnO 0.25 wt% and Ti 3790 ppm (~ TiO_2 0.63 wt%). In particular, it has a Al_2O_3/SiO_2 ratio of 0.047, TiO_2/Al_2O_3 of 0.2, 1000(Th/Zr) of 8.5 and $1000La/TiO_2$ of 16, which fit the chemical profiles of HIMT glass as suggested by Freestone and colleagues [59].

Potash glass

This research has identified only one potash glass object, which is a translucent green glass fragment from Daoye. Potash glass is a compositional group that is spread across South Asia, Southeast Asia and southern China, and is one of the most complicated groups [9]. This compositional group was mainly found at sites dated from late-1st millennium BCE to the first few centuries CE. The Daoye sample slightly post-dates the dominance of potash glass around the South China sea.

The provenance of potash glass remains obscure. Three sub-groups were suggested based on their Al_2O_3 and CaO contents. Generally, the m–K-Ca glass refers to potash glass containing CaO between 3 and 7 wt% and Al_2O_3 below 3 wt %, the m–K-Al glass has CaO below 3 wt% and Al_2O_3 in 3–7 wt%, and the m–K-Ca-Al glass has moderate CaO and Al_2O_3 below 3 wt% [9]. However, the potash glass in this research does not fit in any sub-groups, as it contains K_2O of 15 wt%, Al_2O_3 of 6.5 wt% and CaO of 7.3 wt%. Both Al_2O_3 and CaO are much greater than its counterparts in Southeast Asia [9, 62, 63]. A low Rb (100 ppm) but greater MgO (2 wt%) and Sr content (609 ppm) is also observed in the Daoye sample. The elevated Sr may be associated with its high CaO contents. The Fe_2O_3 of 2 wt% and CuO below detection limit further indicates that iron oxide may have been intentionally introduced to generate the green colour.

Overall, the potash glass from Daoye reveals a different compositional profile compared to the early potash glass around the South China Sea. It is currently difficult to make further discussions due to the small sample size as well as limited comparable research on potash glass in the early 1st millennium CE, although the paucity of potash glass in southwestern Taiwan fits previous observation that potash glass declines from late 1st millennium BCE onwards.

Discussion

Daoye, Doaye South and Wujiancuo were all consumers in the glass exchange network(s); there is no evidence for primary or secondary production in southwestern Taiwan. The analysis of glass objects from Daoye, Daoye South and Wujiancuo indicates the presence of multiple sources of long-distance glass exchange networks in Metal Age Taiwan, as well as around the South China Sea in early-mid 1st millennium CE.

For glass beads, the chemical composition shows a clear transition from the exclusive dominance of m-Na-Al glass at Daoye in early Metal Age, to the co-occurrence of m-Na-Al glass and v-Na-Ca glass at Daoye South and Wujiancuo in the middle Metal Age. Conversely, the glass bangles/earrings reveal an opposite elemental pattern. The early assemblage at Daoye is v-Na-Ca glass, and the glass bangle at Daoye South is made of m-Na-Al glass. Taken together, the m-Na-Al glass indicates the continuing circulation of South Asian made glass in the South China Sea, while the presence of v-Na-Ca glass in early 1st millennium CE demonstrates early and likely indirect contact with West Asian glass production, specifically in Mesopotamia, in this early period.

The sub-groups identified in each compositional group may be linked to the procurement and use of raw materials from different geological locations. Their presence in southwestern Taiwan suggests the possibility of multiple production workshops/centres within a single compositional group. This indicates the complex exchange networks across Taiwan, Southeast, South and West Asia in early-mid 1st millennium CE. Within southwestern Taiwan, the m-Na-Al low Al low Ca sub-group and v-Na-Ca high Cr sub-type appear in both Daoye (1st—sixth century CE) and Daoye South (4th—eighth century CE), suggesting the continuity of similar exchange networks or partners from early to middle Metal Age in this area. The dominance of blue and green colours in the glass objects in this area could be due to the cultural or social preference or the demand of local community, or alternatively as a result of the supply from continuing exchange networks. At Daoye South, the appearance of v-Na-Ca high Li sub-type, although in a small quantity, may suggest more diverse production sources of glass objects were circulated in the middle Metal Age.

For m-Na-Al glass, the dominance of m-Na-Al subtype 1 indicates the participation of Daoye, Daoye South and Wujiancuo in the glass exchange network around the South China Sea and beyond, as it was the most prevalent sub-type in the 1st millennium CE. Evidence of the primary production of m-Na-Al 1 is reported in South India and Sri Lanka [12]. However, the manufacturing location of the new sub-type m-Na-Al low Al low Ca glass remains unclear. A comparison of the contents of Al_2O_3, CaO, B and Li with published data from Taiwan and Southeast Asia [1, 7, 8, 10, 22, 23] shows a complex picture (Figs. 11 and 12). Currently, there is no similar counterparts from other sites in Taiwan. Two samples (AKC01651 and AKC01683 [15]) from Prei Khmeng of 1st—sixth centuries CE in Cambodia possess similar levels of Al_2O_3 and CaO. The two samples also exhibit similar levels of B, Li, Sr and Cs to the m-Na-Al low Al low Ca samples from southwestern Taiwan. It is also noteworthy that some m-Na-Al glass from the slightly earlier site, Phum Snay (350 BCE—200 CE), or the contemporary sites, Sophy and Prei Khmeng, in Cambodia reveals elevated levels of B and Li, although their chemical profiles do not always fit that identified in m-Na-Al low Al low Ca sub-type (Figs. 11 and 12). Based on the current archaeological evidence, it is difficult to assert any direct

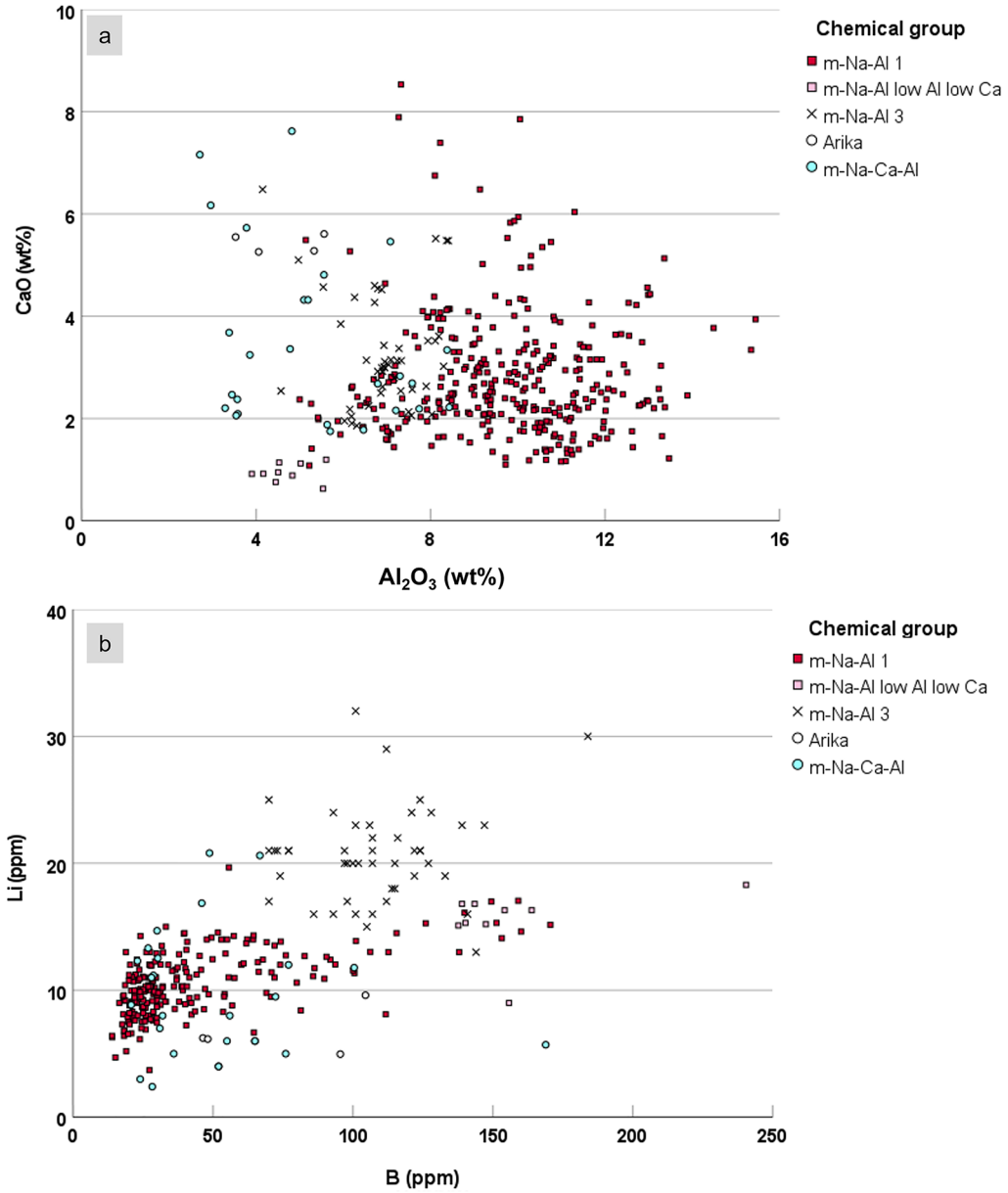


Fig. 11 Bivariate plots of Al_2O_3-CaO and B-Li showing the variations in different sub-groups of mineral soda alumina glass. (The comparative data was from 1,7,8,10,22,23,63)

interaction between Taiwan and Cambodia during this period. The significance of this discovery is to illustrate the complexity of trade networks around the South China Sea in the early-mid 1st millennium CE and to encourage future consideration of exchange relationships and mechanisms from a micro-regional perspective.

Carter has suggested that the exclusive dominance of m-Na-Al sub-type 1 in the 1st millennium CE may reflect the intensified exchange with South Asia, as well as the mass production of m-Na-Al glass in South India and Sri Lanka [1, 2]. It is worthy of future investigation to understand whether the m-Na-Al low Al low Ca sub-type suggests the presence of small-scale glass production workshops which are yet to be discovered or whether it indicates a less controlled recipe or treatment of sand materials with heterogeneous components. Unfortunately, within the study sites, no clear differences

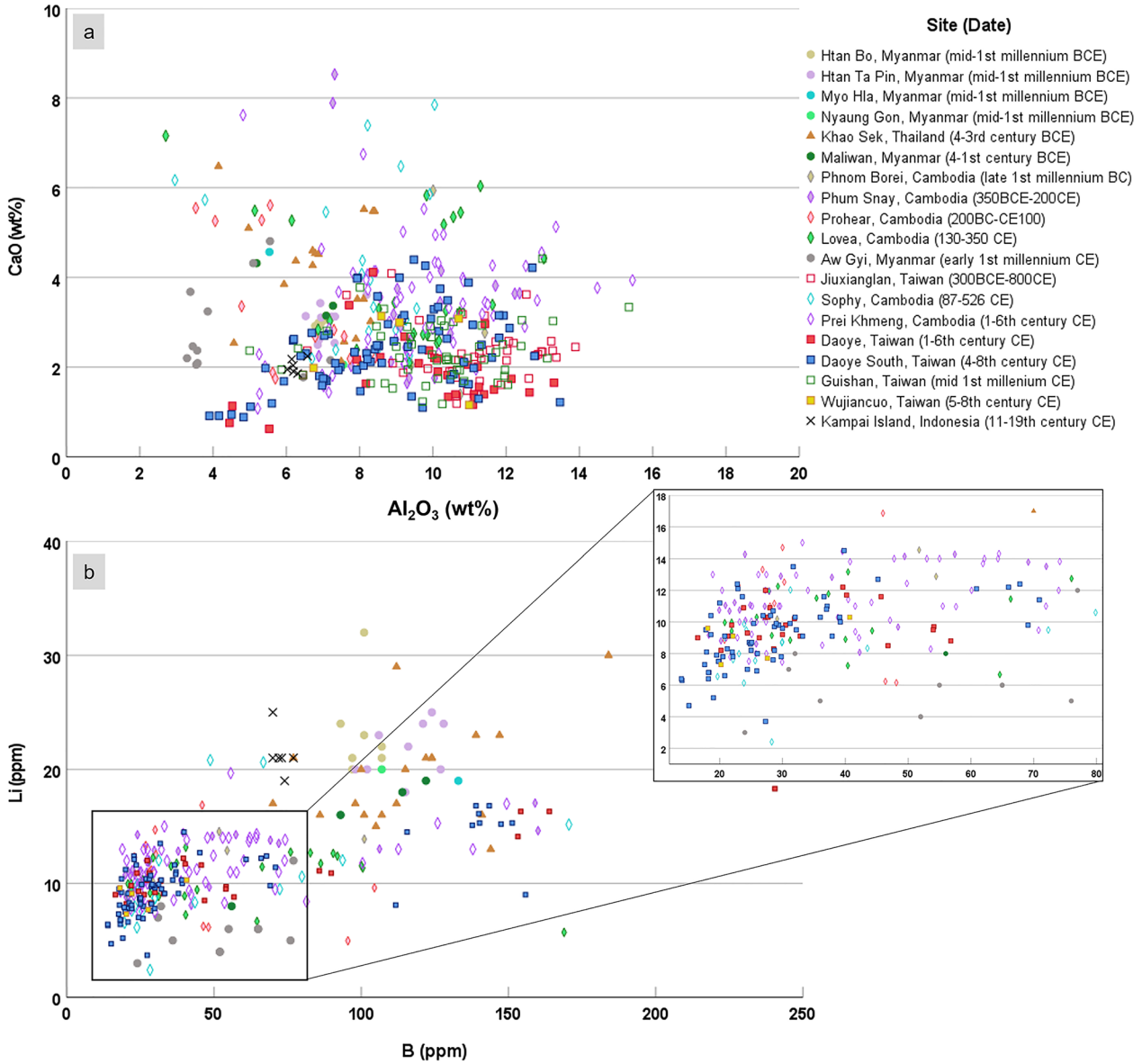


Fig. 12 Bivariate plots of Al_2O_3-CaO and B-Li showing the variations in mineral soda alumina glass from different archaeological sites and varying chronology. (The comparative data was from 1,7,8,10,22,23,36)

of specific contexts can be identified between the two sub-types that can further refine the chronology.

In terms of v-Na-Ca glass, this research provides compelling evidence through elemental and microstructural analysis that the v-Na-Ca glass found in Metal Age Taiwan in early-mid 1st millennium CE has its origins in Mesopotamia, which was part of the Sasanian territories between the third and seventh century CE. Sasanian glass vessels were produced in several locations in Iraq using a v-Na-Ca glass recipe, as revealed by archaeological evidence [44, 47, 48, 64].

Lankton and Dussubieux [17] suggest the possibility of local glass bead production in Southeast Asia using imported v-Na-Ca glass, however the lack of possible production contexts makes it difficult to determine where or if the secondary production of these glass ornaments may have taken place. The Taiwanese assemblage does not suggest evidence of recycling using v-Na-Ca glass, as the low concentration of heavy elements hardly suggest the accumulation of heavy elements from the recycling process. However, in Sasanian territories, archaeological finds of glass production suggest that glass vessel making

was prevalent, but there is little discussion regarding the technology of glass beads and bangles/earrings in West Asia. Around East Asia, Sasanian-style glass *vessels* have been discovered in Japan, Korea and China, and some objects are confirmed to have a v-Na-Ca glass composition, indicating their importation as finished goods from West Asia [65, 66]. V-Na-Ca glass *beads* associated with a Mesopotamian or Sasanian origin have also been found from the late Yayoi to middle Kofun period (2nd—seventh century CE) in Japan, as well as from contemporary sites in Xinjiang, China [67–69]. While a limited number of v-Na-Ca glass *beads* have been reported in Southeast Asia during this early period, there is no mention of Sasanian style glass *vessels* in any archaeological contexts here, although a few opaque mosaic glass fragments and transparent green glass fragments (no information of object styles) with a v-Na-Ca glass composition were reported at Phu Khao Thong (second century BCE—fourth century CE) [18] and Khlong Thom (1st/2nd—seventh centuries CE) [17] in Thailand. As for glass *bangles/earrings*, the assemblages from Daoye represent the sole finds around Southeast and East Asia that possess v-Na-Ca glass composition associated with a Mesopotamian origin. Currently, the existence of secondary glass production during the early to mid-1st millennium CE in South, Southeast Asia and East Asia is poorly documented. Research lacunae persist regarding the long-distance movement of glass materials and the organisation of production or exchange activities in these extensive areas. This makes it a challenge to pinpoint the possible secondary production locations. A few v-Na-Ca glass beads made by the drawn method in Daoye South may suggest a certain technological relationship or knowledge exchange with the South Asian beadmaking tradition. An association between the drawn method and v-Na-Ca glass composition in a wider Asian context was also noted by Lankton and Dussubieux [14].

Another question opens regarding the exchange route of the v-Na-Ca glass in southwestern Taiwan. In China and Japan, scholars suggest that the v-Na-Ca glass may have been imported from Mesopotamia through the overland Silk Road in the north, which connects West Asia and Central Asia to East Asia [67–69]. Archaeological evidence of glass objects and the distribution of glass compositional groups support the idea of a land Silk Road route from West Asia though Central Asia to China, Korea and Japan. Notably, the v-Na-Ca glass of a Central Asian characteristic (slightly greater Al_2O_3 and K_2O than the Sasanian v-Na-Ca glass) and potash glass associated with southern China/South Asia/Southeast Asia can be found in China, Korea and Japan [67, 68, 70]. Lead glass is another compositional group commonly discovered in archaeological sites along China, Korea and Japan, with lead isotope analysis suggests primary production in these three countries [68, 71–74]. This indicates that China, Korea and Japan likely participated in a similar or overlapping exchange network of glass objects during this period.

In contrast, the compositional groups seen at Daoye, Daoye South and Wujiancuo demonstrate a different distribution, with m-Na-Al glass being dominant and lead glass as well as Central Asian-style v-Na-Ca glass absent in the 1st millennium CE in Taiwan. This indicates that southwestern Taiwan was involved mainly in the southern maritime glass exchange network across Southeast and South Asia rather the northern terrestrial Silk Road through continental East Asia. At Daoye South, the co-occurrence of m-Na-Al glass and v-Na-Ca glass in the same burial further reveals that glass beads of the two chemical compositions were acquired, used and then buried at the same time.

It is thought that *indirect* maritime exchange route(s) connecting West, South, Southeast Asia and Taiwan is likely for the occurrence of v-Na-Ca glass in early-middle Metal Age, as there is no evidence of direct South Asian or West Asian influences on the cultural, social or political activities in Taiwan's archaeological record. During this period, overseas exchange in Taiwan is more directly and closely linked to Southeast Asia, as evidenced by the circulation of glass beads, carnelian beads and likely copper-base metal objects and/or metal working technology [75]. On the other hand, it can be seen in Fig. 7 that despite the limited numbers of v-Na-Ca glass in Southeast and South Asia, the majority of early v-Na-Ca glass from contemporary sites in Taiwan, Southeast and South Asia also belong to the Mesopotamia Type 1, suggesting that the appearance of v-Na-Ca glass of a Mesopotamian origin is not exclusive in Taiwan, but occurs along the sea-based networks. V-Na-Ca glass is also found in the contemporary site Khlong Thom (1st/2nd—seventh centuries) in Thailand, and a Mesopotamian or Iranian origin has been suggested [17].

Indeed, maritime long distance exchange routes connecting the southern part of East Asia, Southeast Asia, South Asia and West Asia can be observed from both archaeological and historical records. Close interaction between Taiwan and Southeast Asia since the Neolithic period (circa 3000 BCE—1 CE) has been attested particularly by the circulation of nephrite materials [76, 77]. Exchange links between Southeast Asia and South Asia during the same time period are illustrated by semi-precious stones, bronze vessels/technology and early glass with a potash or m-Na-Al sub-type 3 composition [6, 78–80].

Further westwards, the Persian Gulf served as a gateway connecting Mesopotamia through the Indian Ocean

to India and beyond. Intermittent exchange between South Asia and Mesopotamia can be traced back to the Harappan period around the 2nd millennium BCE, and the interaction between the two areas grew and continued into the Sasanian period [81, 82]. Mesopotamian contact in the Indian sub-continent and Sri Lanka can be inferred by the finds of Roman and Sasanian coins and 'torpedo jars,' a type of storage jars which may have been produced in southern Iraq and Iran [78, 83]. Torpedo jars were widely distributed throughout the Persian Gulf and the Indian Ocean, and were recently found from the Phanom-Surin shipwreck off the shoreline of the Gulf of Thailand in Southeast Asia, dating to the eighth century CE [84, 85].

Archaeological sites predating Daoye, Doaye South and Wujiancuo in Southeast Asia and South Asia also occasionally yielded Roman objects, such as glass, coins and intaglio [14, 78, 86–89]. The single HIMT glass fragment found in this research can be considered as a fortuitous discovery, but nonetheless bears witness to the interconnected maritime exchange networks that existed across Southeast, South, West Asia and likely extended to the Mediterranean during the mid-1st millennium CE. Recent research also suggests that indirect Roman-Southeast Asian links during late 1st millennium BCE to first century CE were mediated through South Asian perspectives, evidenced by Roman objects in port settlements, indicating a shared trading network with South Asian cultural influences [90]. Moreover, the findings at Daoye, Daoye South, and Wujiancuo exhibit a resemblance to the situation observed at the contemporary Khlong Thom site in Thailand. At Khlong Thom, various types of glass, including m-Na-Al glass, m-Na-Ca-Al glass, v-Na-Ca glass, potash glass and Roman natron glass, have been identified, with m-Na-Al, m-Na-Ca-Al, and v-Na-Ca glass being the predominant varieties [17]. The diversity in object types and bead styles at Khlong Thom is greater than that observed at Daoye, Daoye South, and Wujiancuo. This suggests the presence of potentially more active exchange, and likely production activities at Khlong Thom.

In terms of the historical records, the Treatise on Geography (*Dilizhi* 地理志) in the Book of Han (*Hanshu* 漢書), a written record of Han Dynasty in China, documented the maritime trade routes in 111 BCE through Hepu in southeastern China, towards coastal cities along Vietnam, Cambodia, Thai-Malay peninsula and Sumatra in Southeast Asia, arriving at eastern India and Sri Lanka ([91] and see Fig. 37.3 therein). It is mentioned in the text that Chinese merchants brought silk to exchange for beads, glass and semi-precious stones, vividly demonstrating the exchange routes across the South China Sea and Bay of Bengal. Other written sources, such as Ptolemy's *Geography* in the west and the Book of Later Han (*Houhanshu* 後漢書) in the east, also document sporadic contacts between Roman and communities in South and Southeast Asia ([88] and see references therein). It is also worth noting that the northern Thai-Malay peninsula, where Khlong Thom located, might be the location of the Funanese port city, Dunsun or Tunsun (頓遜), mentioned in the Book of Liang (*Liangshu*梁書, 502–557 CE) [92, 93]. It is recorded that thousands of individuals from both the eastern and western regions visited Dunsun daily to engage in the trade of valuable commodities.

These archaeological finds and written records illustrate the dynamic and diverse cross-regional exchange routes connecting coastal communities along West, South and Southeast Asia. In Southeast Asia, previous discussion mostly derived from archaeological finds from the western part of the South China Sea. The identification of Mesopotamian glasses and the only HIMT glass in Taiwan thus provides an excellent case study from the eastern part of the South China Sea in the early to mid-1st millennium CE, linking the island parts of Taiwan/Southeast Asia to the everchanging cross-regional maritime exchange networks in the 1st millennium CE.

Additionally, it is noteworthy that v-Na-Ca glass in the later period exhibits a more complex exchange pattern. Mesopotamian Type 2 glass appeared in Cambodia and Malaysia in late 1st millennium CE, and more diverse sub-types can be observed in Malaysia at the turn of the 2nd millennium CE. This likely suggests a temporal transition of v-Na-Ca glass in Southeast Asia, although a full discussion is beyond the scope of this research. It is worthy of future investigation in order to gain a better understanding of the maritime glass exchange network covering Southeast, South and West Asia from a long-term perspective.

Conclusion

Glass studies around the South China Sea have predominantly focused on glass beads dating from 500 BCE to 500 CE, resulting in a lack of analytical data for later periods. This research presents and contributes new findings from Daoye, Daoye South and Wujiancuo, located in southwestern Taiwan, dating from the first to eighth century CE, using LA-ICP-MS and SEM–EDS for chemical and microstructural analysis, respectively. The study identifies two primary compositional groups, m-Na-Al and v-Na-Ca (or soda plant ash) glass, along with an additional potash glass sample that cannot be classified within any early potash glass sub-groups in the South China Sea region, and a HIMT glass originated in the Roman Mediterranean. M-Na-Al glass is linked to South

Asian glass production, while v-Na-Ca glass indicates a West Asian glassmaking tradition.

For m-Na-Al glass, m-Na-Al sub-type 1 is the dominant sub-group, indicating the widespread use of mass-produced mineral soda glass originating in South India or Sri Lanka. The newly identified type, m-Na-Al low Al low Ca, might provide new insights into the discussion on small-scale production or less controlled recipes of m-Na-Al glass during this period.

In terms of v-Na-Ca glass, this study offers robust evidence for a Mesopotamian or Sasanian primary production origin of the early v-Na-Ca glass in the South China Sea, with little evidence for recycling. The sub-groups identified here demonstrate variations in impurity within the silica sand and plant ash, as well as differences in the use of copper colourant recipes in the blue glass. Additionally, this research provides the first dataset of glass bangles and earrings of a v-Na-Ca composition in the South China Sea region, dating to early-mid 1st millennium CE at Daoye, although the secondary production area remains unclear.

From a regional perspective, this research highlights southwestern Taiwan's involvement in the cross-regional, dynamic and multi-scalar maritime glass exchange networks linking more than eight thousand kilometers across Southeast, South and West Asia. Chronologically, our results suggest a shift in glass compositional groups, from the predominance of m-Na-Al glass in early 1st millennium CE to the co-occurrence of m-Na-Al and v-Na-Ca glass in mid-1st millennium CE. More importantly, through a good number of v-Na-Ca glass samples, this research not only extends the chronological framework for its common occurrence from the previously acknowledged 7th—eighth centuries to the early/mid -1st millennium CE, but also confirms that the early appearance of v-Na-Ca glass around the South China Sea region was not accidental. The presence of the same sub-group at Daoye (1st—sixth century CE) and Daoye South (4th—eighth century CE) further suggests the continuities of overseas exchange networks in southwestern Taiwan from early to middle Metal Age. Overall, this research fills a research gap in the less studied period of early to mid-1st millennium CE for glass circulation in the South China Sea, shedding new lights in mapping the connectedness of maritime glass exchange networks between Taiwan, Southeast, South and West Asia.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-01093-1.

Additional file 1: Figure S1. Radiocarbon dating of Daoye, calibrated using the OxCal v.4.4 software [2] and IntCal20 atmospheric curve [3]. **Figure S2.** Radiocarbon dating of Daoye South, calibrated using the OxCal v.4.4 software [2] and IntCal20 atmospheric curve [3]. **Figure S3.** Radiocarbon dating of Wujiancuo, calibrated using the OxCal v.4.4 software [2] and IntCal20 atmospheric curve [3].

Additional file 2. Sample profiles and chemical composition.

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Author contributions
KW and KL were the project investigator for funding acquisition. KW was responsible for methodology and conceptualisation. KW and YI worked on SEM–EDS analysis. LD carried out LA-ICP-MS analysis. KW and LD worked on data investigation and synthesis. KW prepared the original draft. CT and KL provided the research materials as well as the consultation to the archaeological context. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Competing interests
The authors declare that they have no competing interests.

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