CONTEXTUALIZING A COLLECTION: COMPOSITIONAL, MORPHOLOGICAL, AND TRADE NETWORK INSIGHTS FROM AN IRON AGE COLLECTION OF RARE SOUTHEAST ASIAN GLASS ORNAMENTS

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ABSTRACT

Previous studies of Iron Age (500 BC–AD 500) Southeast Asian glass ornaments have almost exclusively examined glass beads comprising the majority of glass ornament assemblages at Iron Age Southeast Asian sites. When mentioned, other ornament types (e.g., rings, bangles, and earrings) are typically fragmented or in otherwise poor condition. This study is one of the first to report on the elemental compositions of complete rare glass ornaments—specifically, a collection of seven complete glass earrings, five complete glass bangles, and a single spiral ornament. These objects were donated to the University of Oregon for repatriation to Cambodia and are believed to originate from the site of Phum Snay, Cambodia. Using primarily LA-ICP-MS compositional data of six collection objects, we contextualize this collection within the corpus of glass ornaments that circulated in Iron Age Southeast Asia as well as contemporaneous glass trade networks and associated spheres of influence. Results from this analysis identified multiple glass types and subtypes, including potash glass and soda glass. This research is ultimately relevant for its novel compositional and morphological data and insights into the circulation of these rare ornaments within regional exchange networks.

INTRODUCTION

Though glass ornament research in Iron Age (500 BC–AD 500) Southeast Asia is an active field, previous studies have almost exclusively focused on glass beads, leaving a gap in scholarly understandings of rare Iron Age Southeast Asian glass ornament compositions, morphologies, and exchange networks (Carter 2016). This study is one of the first scientific reports examining complete glass earrings, bangles, and a spiral ornament, all likely from the northwest Cambodian site of Phum Snay. Using primarily compositional data from laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), this study contextualizes these rare artifacts within known glass typologies and expands those findings to place the artifacts within contemporaneous glass trade networks and associated spheres of influence. These artifacts' compositions suggest participation within an early South China Sea potash glass exchange network (Bellina 2018a), a later South Asian high-alumina mineral soda glass network, and perhaps the Mekong Interaction Sphere (Carter *et al.* 2021). This work ultimately broadens current understandings of glass in Iron Age Southeast Asia by using compositions and morphologies of rare, understudied artifacts to demonstrate that Iron Age Southeast Asian glass circulation included non-bead ornaments constituting diverse glass types.

BACKGROUND

Phum Snay Collection Contextualization and Background

The glass ornaments under study were purchased in Cambodia by a collector who reported the collection to be from Phum Snay. This collection was subsequently donated to Alison Carter at the University of Oregon to facilitate repatriation to Cambodia's Ministry of Culture and Fine Arts (MOCFA). This repatriation process is currently underway, with a planned donation to the National Museum of Cambodia (NMC) in 2025. Though these artifacts were looted, making it impossible to know this collection's context with certainty, the donor's account and morphological similarities with other ornaments strongly evidence Phum Snay as this collection's original context. Additionally, the extensive looting at Phum Snay and subsequent selling of looted artifacts since the site's rediscovery in 2000 support the collector's claim to the collection's Phum Snay context (O'Reilly *et al.* 2008).

The ethics of working with looted collections and collectors are complex (e.g., Shott and Pitblado 2015). The Society for American Archaeology (SAA) issued a statement in 2018 on collaboration with responsible and responsive stewards of the past (Pitblado *et al.* 2018), and Carter decided to accept this collection following several of the statement's recommendations. First, the collector agreed to donate the entire collection for repatriation to Cambodia and would not benefit financially by doing so (recommendation #4). Second, undergraduate students at the University of Oregon were involved in cataloging and documenting the collection as part of a course on Southeast Asian archaeology and through independent studies. As part of this work, students learned about issues related to looting and repatriation as well as the ethics of working with collectors and looted collections (recommendation #1). Students were also able to study the collection to (a) verify the objects are not fakes, (b) determine whether the artifacts have an affiliation with documented archaeological cultures in Cambodia, and (c) provide context on the collections that may have otherwise been lost (recommendation #3). In doing so, not only were students able to access a valuable learning opportunity doing collections-based research, but undergraduates also provided background information on the collection to assist the staff at MOCFA and the NMC in accessioning these objects. Although the ideal situation would be that these objects had never been looted in the first place, we feel their study can still provide valuable information for future scholars.

Phum Snay is an Iron Age cemetery site dating to 207 BC–AD 239 in Banteay Meanchey Province in northwest Cambodia (see Figure 1) (O'Reilly and Pheng 2001; O'Reilly 2004; O'Reilly *et al.* 2004; O'Reilly *et al.* 2006: 190; O'Reilly *et al.* 2008). Road construction in 2000 connecting Phum Snay to National Route 6 unearthed multiple human burials (O'Reilly 2004: 129; O'Reilly *et al.* 2006: 188; O'Reilly *et al.* 2008). Widespread looting ensued, spurring the Royal University of Fine Arts (RUFA) to conduct scientific excavations at Phum Snay (O'Reilly *et al.* 2008; Carter 2013: 71). Phum Snay is archaeologically significant in part for its large number of diverse Iron Age Southeast Asian artifacts (e.g., weaponry, beads and other personal ornaments made of copper-based metals, shell, stone, and glass) offering a unique insight into Iron Age Southeast Asian culture (O'Reilly *et al.* 2008; Nojima 2013). Evidence for sharp and blunt force lesions on crania from Phum Snay and the uniquely high number of weapons found in burials suggest violence was prevalent (O'Reilly *et al.* 2008; Domett *et al.* 2011).

Glass Exchange in Iron Age Southeast Asia

Mainland Southeast Asia's Iron Age spans approximately 500 BC–AD 500 and is characterized by significant socio-economic and socio-political changes catalyzed by the expansion of intraregional and interregional exchange networks and social, cultural, and technological interaction with South and East Asia on a large scale for the first time (Bellina and Glover 2004; Stark 2006; Lankton and Dussubieux 2013; Higham 2016). Consequently, analysis of Iron Age ornaments offers an opportunity to learn about contemporaneous trade networks circulating such artifacts.

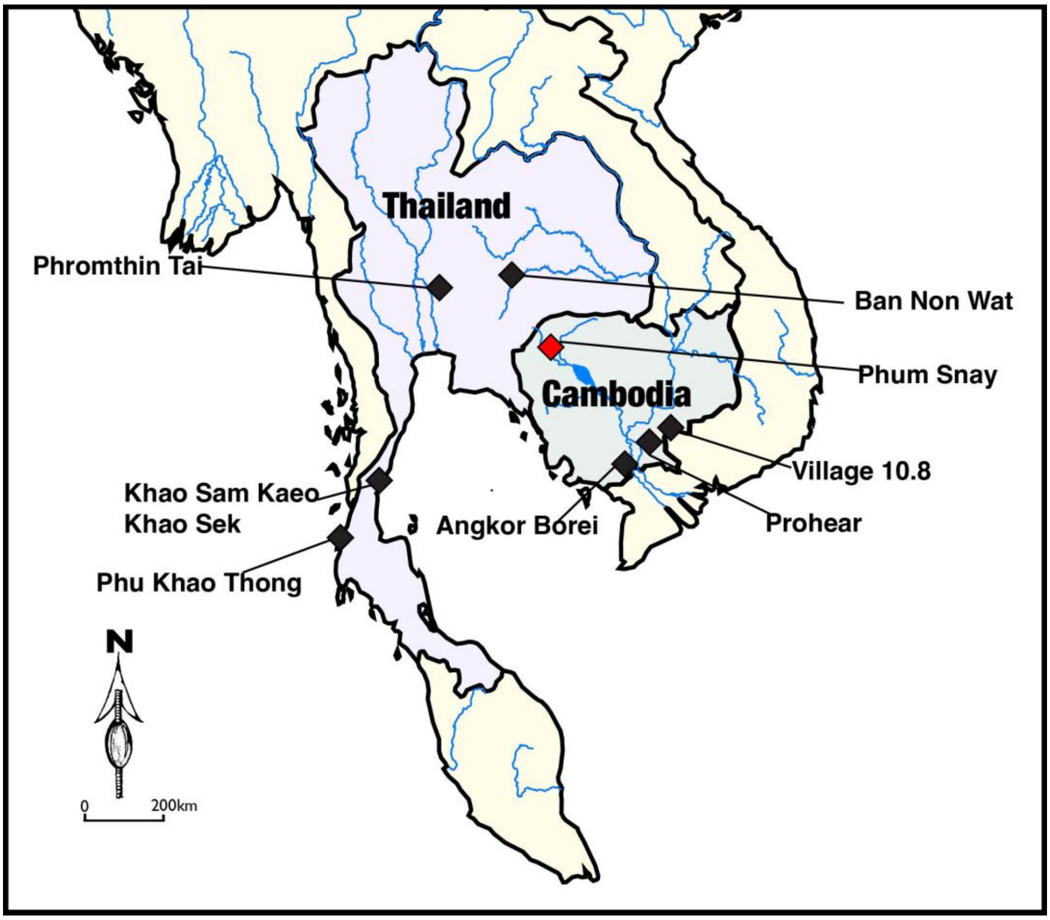

Figure 1. Sites mentioned in the text, including Phum Snay. Modified from Carter (2015).

Southeast Asia's participation in the Maritime Silk Road by around 400 BC facilitated glass trade both as a raw product for local production and as finished objects likely originating in East and South Asia (Lankton and Dussubieux 2013: 415; Bellina 2014: 345; Bellina 2018a: 8). Lankton and Dussubieux (2013: 415–416) use early Asian glass and other prestige goods circulation to establish routes for later glass trade's swift expansion across Asia.

Cultural interaction among elite members of society via far-reaching trade networks of prestige goods such as glass ornaments (Carter 2013: 6–7) relates directly to the socio-political development that characterizes Southeast Asia's Iron Age (Lankton and Dussubieux 2013: 415). For example, elites likely controlled ornament trade, which both strengthened interregional socio-economic relationships and provided elites with material representations of their socio-political status (Lankton and Dussubieux 2013: 415). Because of this close relationship between trade and economic and cultural power, glass ornaments such as beads, bangles, and earrings are uniquely useful artifacts to archaeologically research how exchange networks resulted from and facilitated social, cultural, and political interactions in Iron Age Southeast Asia (Theunissen 2003; Hung *et al.* 2007; Reinecke *et al*. 2009: 120–122; Dussubieux and Gratuze 2010: 257; Carter 2015: 733; Bellina 2018b; Carter *et al.* 2021: 32).

Glass ornaments first appeared in Southeast Asia as beads, bangles, and earrings around 500 BC (Dussubieux and Gratuze 2010: 247; Lankton and Dussubieux 2013: 415;

Dussubieux and Bellina 2017). Multiple exchange networks with different glass compositions circulated glass in Southeast Asia within regional interaction spheres (Dussubieux *et al.* 2012; Lankton and Dussubieux 2013; Carter 2016). One of Southeast Asia's earliest major glass ornament trade networks, dating to the late centuries BC, circulated potash glass objects within a likely pre-existing prestige goods network operating mainly along the South China Sea coast that included craft products such as Dongson drums and nephrite (jade) ear ornaments (Hung *et al.* 2007; Lankton and Dussubieux 2013: 416; Carter 2015: 735, 748; Carter 2016; Bellina 2018a; Calo *et al.* 2020; see also Dussubieux *et al.* 2012). Although it's unclear where potash glass was produced, Southeast Asian workshops may have produced ornaments of various potash compositions in Khao Sam Kaeo and Phu Khao Thong, Thailand and also in Arikamedu, India (Lankton and Dussubieux 2006: 136–137; Dussubieux 2016: 106). Notably, few potash glass artifacts have been found at sites throughout the Mekong Delta and at later inland Iron Age settlements (e.g., Phum Snay), evidencing that such settlements likely were not "major participants" in this early South China Sea littoral exchange network (Carter 2015: 748–749, 751).

Following increased interaction with South Asia during the first few centuries AD, mass-produced monochromatic drawn glass beads made from high-alumina mineral soda glass likely produced in South Asia became more widely circulated across Southeast Asia at both littoral and inland sites (Dussubieux *et al.* 2010; Lankton and Dussubieux 2013: 440; Carter 2015: 748–749; Carter 2016; Carter *et al.* 2021). Bellina and Glover (2004: 80, 83) describe this increased contact between South Asia and Southeast Asia specifically as Phase II spanning AD 100–300 and state that "Indian influences into Southeast Asia were multiple and did not originate in any one area." These two networks do not appear to have overlapped with one another, as sites with potash glass ornaments rarely have high-alumina mineral soda glass ornaments and vice versa (Carter 2015; Lankton and Dussubieux 2013).

In sum, soda alumina and potash glass are the most common glass types in Iron Age South and Southeast Asia, most commonly found as beads and bangles as well as earrings and other "small personal ornaments" (Lankton and Dussubieux 2006: 121; Dussubieux and Gratuze 2010: 247; Carter 2013: 293; Dussubieux 2016: 95, 106).

Previous Work on Glass Ornaments from Phum Snay

As the objects in this current study are likely from Phum Snay, this section summarizes previous studies of glass objects from the site to contextualize this collection. Though ring, earring, and bangle pieces have been found in context, a significant amount of Phum Snay's studied materials lack secure provenience (Carter 2013: 306, 309). Initial studies by Gratuze (2005) and Ly (2007) analyzed 31 glass beads looted and sold by villagers and identified primarily high-alumina soda glass and a small number of dark blue beads made from plant-ash soda lime glass, a composition linked to Middle Eastern glass production. A later study of 75 glass beads from the RUFA excavations by Song (2010) also identified primarily high-alumina soda glass beads but found a small number (n=16) of potash glass beads and four beads classified as mineral soda lime glass as well. It's possible the latter may actually be a composition designated as high-alumina soda glass with variable amounts of alumina and lime (m-Na-Ca-Al), although as exact compositions were not provided, the four beads' glass type cannot be verified. M-Na-Ca-Al glass circulated widely in Southeast Asia and may have been produced at Arikamedu in eastern South India, an unknown location in Sri Lanka, and Khlong Thom, Thailand (Dussubieux *et al.* 2012; Lankton and Dussubieux 2013: 436; Dussubieux *et al.* 2025). Carter (2010, 2013) also undertook a study of glass objects from the RUFA investigations. The majority of glass beads in this study (n=26) were made from high-alumina soda glass. One dark blue bead had a plant ash soda-lime composition similar to that identified by Ly (2007). Three blue ring/earring objects were made from a mineral potash glass with variable amounts of alumina and lime (m-K-Ca-Al). Additional glass beads and ornaments were identified by a Japanese-Cambodian team working at Phum Snay from 2007–2010, but these objects have not yet undergone compositional analysis (Lapteff 2006, 2007; Miyatsuka and Yasuda 2010).

Based on her examination of the complete RUFA Phum Snay collection, Carter (2010, 2015) has proposed that the majority of the glass bead assemblage at Phum Snay was comprised of monochromatic drawn high-alumina mineral soda glass beads. An examination of regional patterns of glass artifact distribution within Cambodia and Thailand has highlighted differences between sites that were dominated by potash glass versus those with a majority of high-alumina mineral soda glass beads (Carter 2015). Sites with large quantities of potash glass beads seem to be affiliated with the aforementioned South China Sea exchange network. In contrast, sites with a predominance of high-alumina mineral soda glass beads appear to be affiliated with a different exchange network. Carter *et al*. (2021) have proposed this shift may be related in part to the growth of a major urban center in the Mekong Delta that circulated high-alumina mineral soda glass beads and ornaments to sites farther inland, like Phum Snay, through a "Mekong Interaction Sphere." Several additional sites in northwest Cambodia—including Phum Sophy, Lovea, and Prei Khmeng—as well as northeast Thailand also appear to be part of this glass exchange network (Carter *et al.* 2023).

Objects in this Study: Morphology, Measurements, and Object Comparison

The current study includes 13 glass ornaments comprising seven earrings (Figures 2–4), five bangles (Figures 8 and 9), and a spiral ornament (Figure 10), six of which (three earrings, two bangles, and the spiral ornament) have been compositionally analyzed using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) by Laure Dussubieux at the Field Museum's Elemental Analysis Facility. We extrapolate the glass compositions of analyzed collection artifacts to unanalyzed collection artifacts due to morphological similarities. The earrings in this study are an artifact type scholars and collectors frequently describe as an earring, a typology we use to be consistent while acknowledging these objects' unknown use. Additionally, Appendix B contains full measurements, shape typologies, and *Munsell Bead Color Book* color typologies of all collection artifacts. Appendix C contains pictures of the collection artifacts—including photos not included in this article—as well as diagrams of how object measurements were made. In the figures that follow, objects in this collection have ID numbers beginning with "UOJF," and museum objects used to draw comparisons are labeled with their museum's name and accession number.

The collection's seven earrings (Figures 2–4) are uniform in shape: a piece of glass bent into a roughly circular U with the ornament getting thinner from its midpoint toward both ends (Figure 2b). The inside of the artifact is flat while a pointed ridge runs along the outside of the artifact so that the objects are faceted on both sides (Figure 2a). The artifacts range in size, with widths ranging between 14.42 mm and 27.45 mm. The earrings are all translucent and variations of either amber or blue-green.

These earrings are morphologically similar to unprovenanced glass artifacts collected at Phum Snay (Tranet 2010: 74), though Tranet refers to this artifact type as nose rings. Additionally, earrings morphologically similar to this collection's earrings reportedly from Vietnam at the Metropolitan Museum of Art (Figures 5 and 6) demonstrate that morphologically similar glass earrings were circulating in Iron Age Southeast Asia, though to the best of our knowledge, this artifact type hasn't been studied scientifically (The Metropolitan Museum of Art (n.d.a, n.d.b). These earrings differ morphologically from simpler earrings from Phum Snay (Tranet 2010: 73–75; Carter 2013: 309; Song 2010: Figure 7), Phromthin Tai, and Ban Non Wat (Carter 2013) (Figure 7). For example, some earrings at Phum Snay maintain the same circ ular U morphology, but their cross section is circular or the width of the earring doesn't decrease as it nears the ornament's end (Tranet 2010: 73–75; Carter 2013: 309).

Figure 2. UOJF0308, UOJF0309, and UOJF0310.

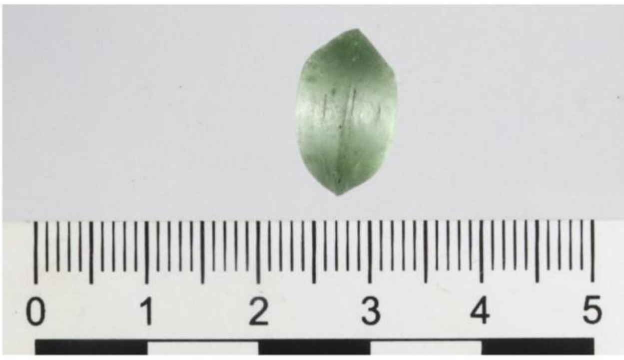

Figure 2a. UOJF0310 facets.

Figure 2b. UOJF0310 narrowing from center.

Figure 3. UOJF0307 and UOJF0306.

Figure 4. UOJF0311 and UOJF0312.

Photos in Figures 2–4 by Alison Carter.

Figure 5. The Metropolitan Museum of Art (a). Accession Number 2004.256

Figure 6. The Metropolitan Museum of Art (b). Accession Number 2004.257

Figure 7. Comparative simpler earrings from excavated contexts. A. and B.: Earring fragments from Phum Snay, Cambodia. C.: Earring fragment from Phromthin Thai, Thailand. D.: Earring from Ban Non Wat, Thailand.

Photos in Figure 7 by Alison Carter.

The collection's five bangles (Figures 8 and 9) adhere to Dussubieux and Bellina's (2018: 28) semi-circular A bangle typology, with variation in bangle thickness, texture, and edge roundness. The bangles range in size, with exterior diameters ranging from 61.45 mm to 66.90 mm. The bangles are all translucent and are either dark blue (two bangles) or light turquoise blue (three bangles). The bangles have no seam and may have been produced with a jointless method (Kanungo 2021: 7–8).

Figure 8. UOJF0314.

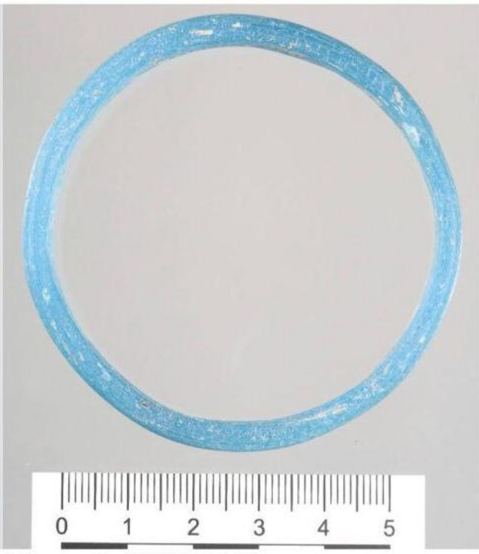

Figure 9. UOJF0318.

Figure 10. UOJF0313.

Figure 11. The Metropolitan Museum of Art (c). Accession Number 2004.258a, b

Photos in Figures 8–10 by Alison Carter.

As with the collection earrings, the collection bangles are morphologically similar to glass bangles from Phum Snay (Tranet 2010: 75), blue potash glass bangles from Ban Non Wat, Thailand (Carter and Lankton 2012: 7), and Khao Sam Kaeo and Khao Sek (specifically, semi-circular A and B bangles) on the upper Thai-Malay Peninsula (Dussubieux and Bellina 2018: 26). However, transparent turquoise-blue bangles and dark blue bangles are rare in Khao Sek's glass assemblage, constituting ~5 % or less of the glass bangle assemblage (Dussubieux and Bellina 2018: 26).

This study's spiral ornament (Figure 10) type has been found multiple times at Phum Snay, although it's been misidentified as a stone artifact (Nojima 2013). The object (unknown purpose) is an opaque turquoise disk flat on one side with notches along both sides of its outer edge. The collection's spiral ornament has a maximum diameter of 52.07 mm, similar in size to that reported by Nojima (2013: 177).

As with both the collection earrings and bangles, other morphologically similar spiral glass ornaments from Phum Snay have been reported by Tranet (2010: 73). Additional similar spiral ornaments (both with and without edge decoration), reportedly from Vietnam, are at the Metropolitan Museum of Art (Figure 11) as well as on auction websites reporting the ornaments to be from the Ban Chiang culture and Thailand/Cambodia more generally (The Metropolitan Museum of Art (n.d.c); 1stdibs (n.d.); Pinterest (n.d.)). This artifact also bears a resemblance to spiral or comma-shaped ornaments found at Ban Don Ta Phet and Khao Sam Kaeo, Thailand (Glover and Bellina 2011: 30–31). Furthermore, Borell and Dussubieux (2022: 36–37, 42) describe a Sri Lankan translucent turquoise potash (m-K-Ca-Al compared to this collection's m-K-Al ornament) artifact with edge serrations and perhaps a spiral shape (half of the artifact is missing). The authors date the artifact between 200 BC–AD 200 and use the ornament to argue for trade relationships between South Asia, Southeast Asia, and even the South China Sea (Borell and Dussubieux 2022: 33, 52). In sum, the spiral artifact type is established in Southeast Asia and perhaps has related styles in South Asia.

METHODS

In addition to morphological examinations, a subset of the collection underwent compositional analysis using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) by Laure Dussubieux at the Field Museum's Elemental Analysis Facility. This method was chosen as no sample preparation is required, and LA-ICP-MS is virtually non-destructive (Dussubieux *et al.* 2009). Further discussion of this technique can be found below and in Dussubieux *et al.* (2009). Appendix A contains all analyzed glass artifacts' LA-ICP-MS compositional results. Major elements are listed in weight percent (wt%), and minor and trace elements are listed in parts per million (ppm).

The analyses were carried out with a Thermo ICAP Q Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) connected to an ESI-Elemental Scientific Lasers NW213 laser for direct introduction of solid samples. The parameters of the ICP-MS are optimized to ensure a stable signal with a maximum intensity over the full range of element masses and to minimize oxides and double ionized species formation (XO^+/X^+ and $X^{++}/X^+ <$ 1–2 %). For that purpose, the argon flows, the RF power, the torch position, the lenses, the mirror, and the detector voltages are adjusted using an auto-optimization procedure.

For heightened sensitivity, helium is used as a gas carrier in the laser. The laser ablation parameters not only have an effect on the method's measurement sensitivity but also on damage to the sample. To be able to determine elements with concentrations in the range of ppm and below while leaving a trace on the surface of the sample invisible to the naked eye, we use the single point analysis mode with a laser beam diameter of 100 µm, operating at 80 % of the laser energy (0.1 mJ) and at a pulse frequency of 20 Hz. We use a 20-second pre-ablation time primarily to eliminate the transient part of the signal and secondarily to ensure that possible surface contamination or corrosion don't affect the analysis results. For each glass sample, the average of four measurements corrected from the blank is considered for the calculation of concentrations.

To improve reproducibility of measurements, the use of an internal standard is required to correct possible instrumental drifts or changes in ablation efficiency. The element chosen as an internal standard has to be present at a relatively high concentration so its measurement is as accurate as possible. In order to obtain absolute concentrations for analyzed elements, the concentration of the internal standard must be known. The isotope silicon-29 was used for internal standardization. Concentrations for major elements, including silica, are calculated assuming the sum of their concentrations in weight percent in glass is equal to 100 % (Gratuze 2016).

Fully quantitative analyses are possible by using external standards. To prevent matrix effects, the composition of standards has to be as close as possible to that of the samples. Three different standards are used to measure major, minor, and trace elements. The first external standard is a standard reference material (SRM) manufactured by NIST: SRM 610, a soda-lime-silica glass doped with trace elements in the range of 500 ppm. Certified values are available for a very limited number of elements. Concentrations from Pearce *et al.*

(1997) are used for the other elements. The second series of standards was manufactured by Corning. Glass B and D are glasses that match compositions of ancient glass (Brill 1999: 544).

RESULTS

Glass typing and subtyping the six analyzed artifacts representative of the larger collection of thirteen ornaments using LA-ICP-MS compositional data identified two potash glass artifacts and four soda glass artifacts. Both glass types were fluxed with a mineral source of either potassium or soda due to their magnesia (MgO) concentrations measuring less than 1.5 wt% (as compared to a vegetal source with more than 1.5 wt% MgO) (Sayre and Smith 1967: 281). Comparison of wt% abundance of potassium oxide/potash (K_2O) and soda (Na_2O) identified the light blue bangle (UOJF0318) and the spiral ornament (UOJF0313) as potash-fluxed, while the mineral soda-fluxed glass ornaments included the dark blue bangle (UOJF0314) and earrings (UOJF0307, UOJF0308, and UOJF0311) (Figure 12). M-Na-Al and potash glass also include six and three subtypes, respectively, distinguished by trace elements and discussed later in this article (Dussubieux *et al.* 2010: 1646; Dussubieux 2016: 99; Kanungo and Dussubieux 2021). See Table 1 for a summary of compositionally analyzed artifacts' glass type, object type (e.g., earring), and color.

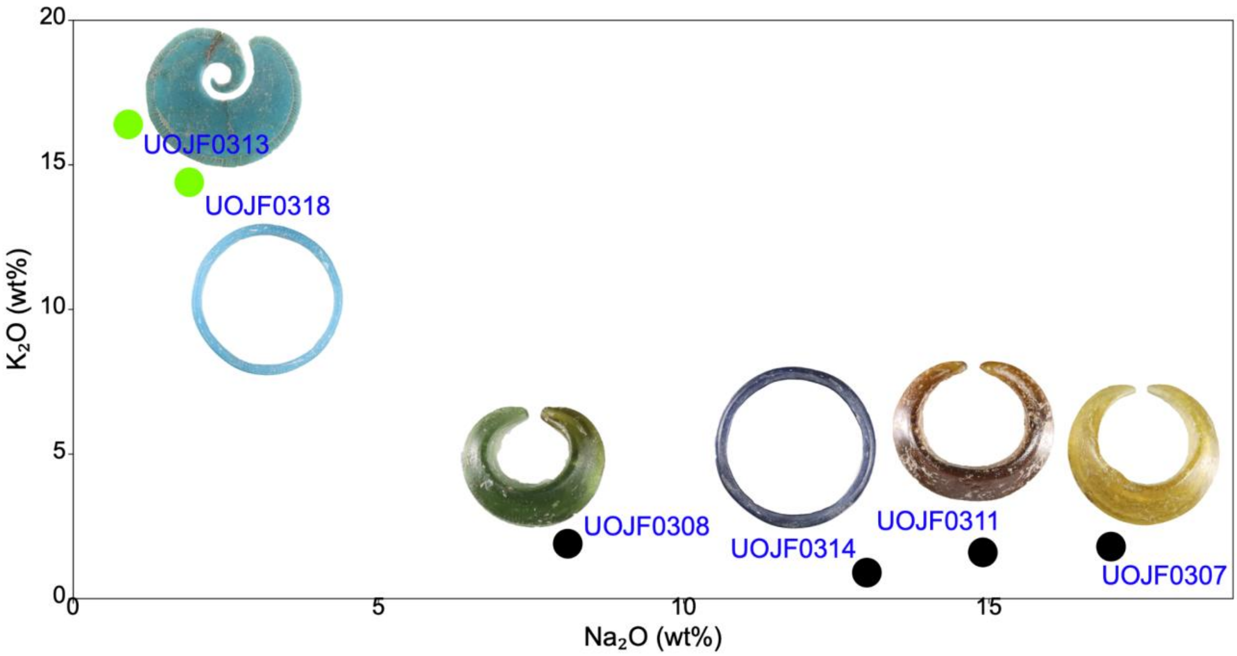

*Figure 12. Biplot of potash (K_2O) and soda (Na_2O) concentrations to distinguish between main glass compositions. *Artifacts not to scale. Artifact photos by Alison Carter.*

Table 1. Summary of compositionally analyzed artifacts' glass type, object type, and color.

	UOJF0307	**UOJF0308**	**UOJF0311**	**UOJF0313**	**UOJF0314**	**UOJF0318**
Object type	Earring	Earring	Earring	Spiral ornament	Bangle	Bangle
Color	Translucent Amber (10.0YR 5/8 Butterscotch)	Translucent Blue-Green (2.5GY 4/4 Olive Green)	Translucent Amber (10.0YR 4/8 Golden Brown)	Opaque Turquoise Blue	Translucent Dark Blue (10.0B 2/4 Dark Navy)	Translucent Turquoise Blue (5.0B 5/7 Bright Blue)
Flux type	Mineral	Mineral	Mineral	Mineral	Mineral	Mineral
Glass type	Soda	Soda	Soda	Potash	Soda	Potash
Glass subtype	m-Na-Al 1	m-Na-Al 1	m-Na-Al 1	m-K-Al	m-Na-Ca-Al	m-K-Ca-Al

Potash Glass Collection Artifacts

Two artifacts—the light blue bangle (UOJF0318) and the turquoise spiral ornament (UOJF0313)—were identified as belonging to the potash glass group by their high K_2O (~14–16 wt%) (Figure 12). Dussubieux (2016: 99–100) has identified three potash glass subtypes based on their variable constituent amounts of Al_2O_3 (alumina) and CaO (lime), as well as trace elements within the potash source (see Liu *et al.* (2013) for more information on rubidium and strontium as trace elements in potash glass). Because Al_2O_3 wt% is high and CaO wt% is low, UOJF0313 is classified as low lime—high alumina (m-K-Al) glass (Dussubieux 2016: 99). M-K-Al glass was used to make beads and bangles and has been identified at Khao Sam Kaeo as well as other sites in Thailand, Myanmar, and Cambodia (see Carter 2016; Dussubieux and Bellina 2018; Dussubieux *et al.* 2020).

In contrast, UOJF0318's CaO and Al_2O_3 are both less than 3 wt%, classifying this artifact as the moderate lime and alumina (m-K-Ca-Al) glass subtype (Dussubieux 2016: 99). This glass subtype was used to produce bangles at the peninsular Thai site of Khao Sam Kaeo and has been found at many sites in South and Southeast Asia from approximately the third to second centuries BC to the fourth century AD (Carter 2016; Dussubieux *et al.* 2012). Additionally, Carter (2013: 334) mentions the presence of m-K-Ca-Al glass ring/earring fragments found at Phum Snay, supporting our hypothesis that these collection objects likely originated from Phum Snay. Comparison against mineral potash artifacts from Cambodia (including ring/earring fragments from Phum Snay) and Thailand confirms these groupings (Figure 13) (Carter 2010, 2013; Dussubieux and Bellina 2018).

The two potash artifacts in study are consistent with potash glass objects from Thailand and Arikamedu, India (e.g., their translucency and light turquoise color) (Dussubieux 2016: 103–104). As a note, Dussubieux describes potash artifacts as "transparent," while the artifacts in this study adhere most closely to a "translucent" or "opaque" diaphaneity. This translucent light turquoise color was likely from added copper, a common colorant in transparent light blue/green potash glass (Dussubieux 2016: 103–104). Indeed, both UOJF0313 and UOJF0318 have elevated concentrations of CuO (2.6 wt% and 1.1 wt%, respectively, as compared to the mineral soda artifacts' 0.0 wt%–0.1 wt% CuO).

Soda Glass Collection Artifacts

Four collection artifacts—UOJF0307, UOJF0308, UOJF0311, and UOJF0314 (three earrings and one bangle)—were identified as belonging to the mineral soda glass group by their high Na_2O (~8–17 wt%) (Figure 12). As noted earlier, soda glass is one of the two most common glass types in Iron Age South and Southeast Asia, including in previous studies at Phum Snay, in important part due to South Asia's abundance of raw materials used to make soda glass as well as South Asia's intensive glass trade with Southeast Asia (Gratuze 2005; Ly 2007; Carter 2010; Dussubieux *et al.* 2010: 1646; Song 2010; Carter 2013: 288; Dussubieux and Gratuze 2013; Lankton and Dussubieux 2013; Carter 2015: 745; Carter 2016). UOJF0307, UOJF0308, and UOJF0311 (the three earrings) have soda ranges between ~8–17 wt% and alumina ranges between ~7–11 wt%, identifying them as high alumina soda glass. UOJF0314, the navy bangle, falls within that soda range but has lower alumina wt% outside the aforementioned range, a compositional difference we return to shortly.

Scholars have identified six distinct soda alumina glass subgroups differentiated by variable constituent amounts of calcium, magnesium, uranium, barium, strontium, zirconium, and cesium (Dussubieux *et al.* 2010: 1646; Kanungo and Dussubieux 2021). In order to determine which subgroup the artifacts in this study fall into, a principle components analysis (PCA) using these elements was performed comparing the artifacts in this study against examples of different m-Na-Al subgroups (Figure 14). The comparative dataset included m-Na-Al 1 objects from Prei Khmeng, Cambodia; m-Na-Al 2 glass from Chaul, India; m-Na-Al 3 glass from Khao Sam Kaeo, Thailand and Maliwan, Myanmar; and m-Na-Al 4 glass from Kota Kareueng, Indonesia and Bukit Hasang, Indonesia (Dussubieux 2009; Dussubieux *et al.* 2010; Carter 2013; Dussubieux and Bellina 2018; Dussubieux *et al.* 2020). M-Na-Al 5 and 6 objects weren't included in the PCA because

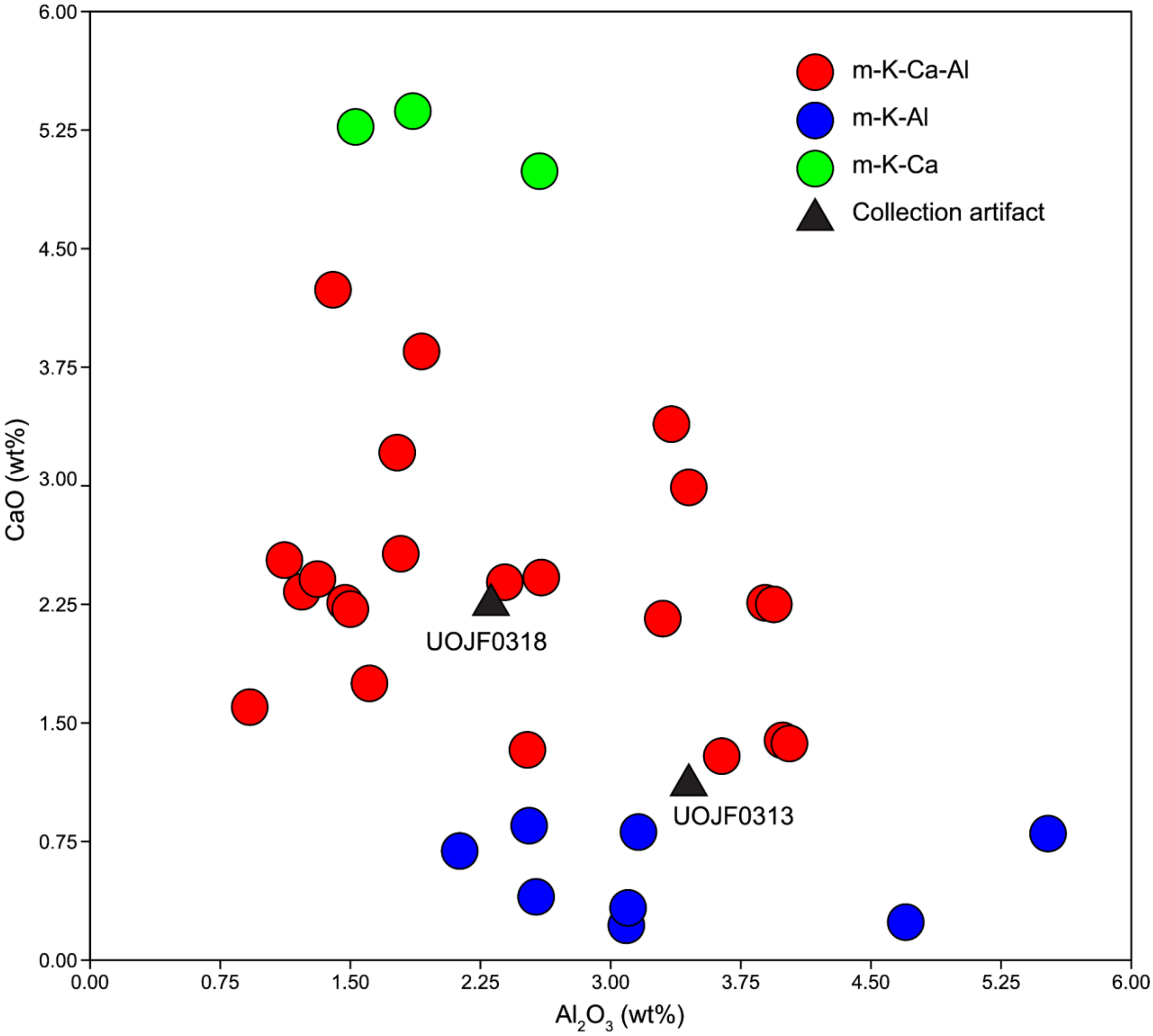

Figure 13. Lime and alumina biplot to identify potash glass subtype. Comparative data from Phum Snay, Cambodia (Carter 2010, 2013) and Khao Sek, Thailand (Dussubieux and Bellina 2018).

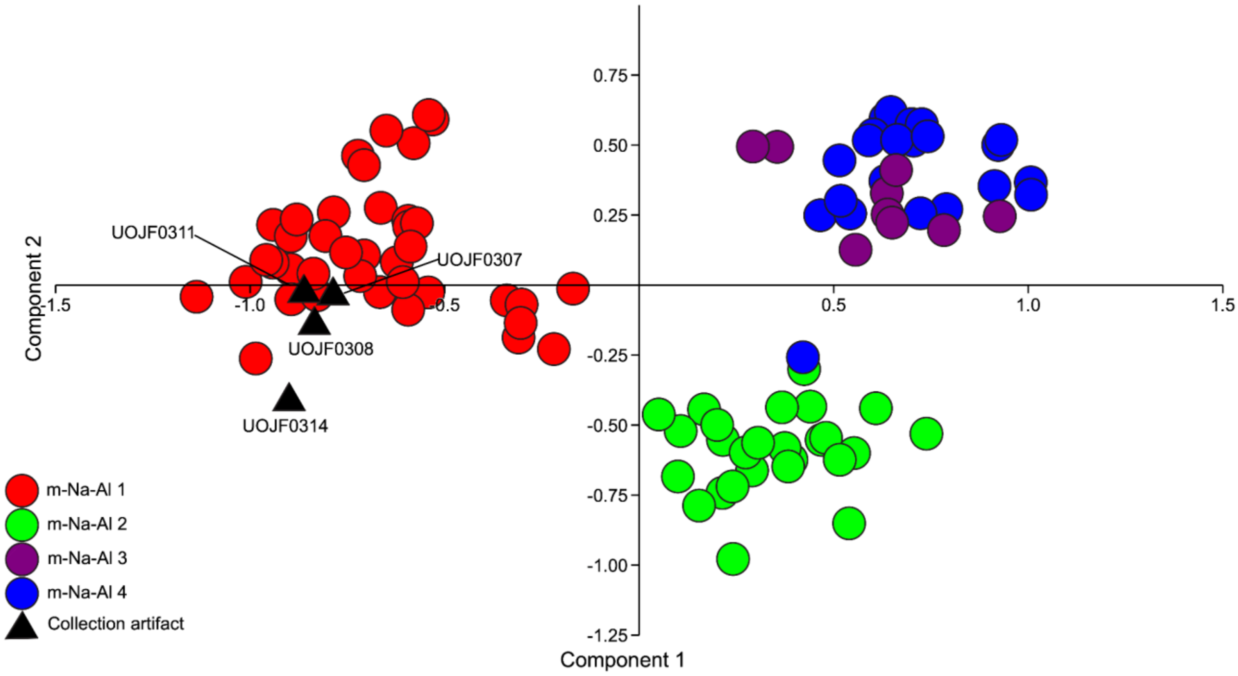

Figure 14. PCA to determine m-Na-Al glass subtype.

m-Na-Al 5 has only been found outside of South and Southeast Asia, and m-Na-Al 6's provenience is still unknown (Dussubieux *et al.* 2010: 1652; Kanungo and Dussubieux 2021: 503). As evident in the PCA, the glass earrings (UOJF0307, UOJF0308, and UOJF0311) plot cleanly into the m-Na-Al 1 subgroup. M-Na-Al 1 glass is characterized by low uranium concentrations and high barium concentrations (lU-hBa), was likely produced in Sri Lanka and/or South India, was primarily used to produce monochromatic glass beads, and, as mentioned earlier, was widely traded in South and Southeast Asia during the first millennium AD (Dussubieux *et al.* 2010: 1650–1651). Because high-alumina mineral soda glass constitutes the majority of Phum Snay's glass assemblage (Carter 2015: 745), this collection's high-alumina mineral soda glass artifacts support our hypothesis that Phum Snay or a nearby site is this collection's soda alumina glass's original context (Carter *et al.* 2023).

Additionally, the colors of the three earrings (UOJF0307, UOJF0308, and UOJF0311) are unusual for their glass type. UOJF0307 and UOJF0311 were likely colored amber with a ferri-sulfide chromophore, but we cannot be sure because LA-ICP-MS cannot identify sulfur (Schreurs and Brill 1984; Paynter and Jackson 2018). Additionally, UOJF0307's and UOJF0311's heightened Fe_2O_3 compositions support a ferri-sulfide chromophore as a colorant (see Appendix A). Furthermore, UOJF0308's translucent green glass may be due to iron intentionally added as a colorant or included unintentionally as an impurity in sand used to make the glass (Henderson 1985: 283).

Notably, the dark blue glass bangle (UOJF0314) plots away from the m-Na-Al 1 cluster. This bangle was colored with cobalt (564 ppm), a coloring agent not used in m-Na-Al 1 glasses (Dussubieux *et al.* 2010: 1650; Carter 2016: 23). Consequently, UOJF0314 appears to belong to a different subtype of mineral soda glass: mineral soda glass with moderate amounts of alumina and lime (m-Na-Ca-Al). This glass type is found across mainland Southeast Asia in Cambodia, Vietnam, Thailand, the western coast of the Thai-Malay peninsula, and in Indonesia during the Iron Age, and m-Na-Ca-Al glass may have been produced and/or worked in the Thai peninsula, eastern South India, or Sri Lanka starting in the middle of the Iron Age (the early period from the third century BC through the fourth century AD) (Dussubieux and Gratuze 2010: 254; Dussubieux *et al.* 2012: 323; Lankton and Dussubieux 2013; Carter 2016: 23; Dussubieux *et al.* 2025). M-Na-Ca-Al glass closely resembles Arika glass produced in Arikamedu, South India (Dussubieux and Gratuze 2013). Like both potash and high-alumina soda glass, m-Na-Ca-Al glass contains magnesia less than 1.5 wt%, while lime and alumina amounts differ greatly across artifacts (Dussubieux and Gratuze 2010: 252; Dussubieux *et al.* 2012: 320–321). In contrast to high-alumina glass with alumina higher than 8 wt% and potash lime concentrations between 3–7 wt%, m-Na-Ca-Al glass lime and alumina concentrations can both reach 7 wt% (Dussubieux and Gratuze 2010: 252; Dussubieux *et al.* 2012: 321; Dussubieux and Gratuze 2013: 405; Dussubieux 2016: 99). M-Na-Ca-Al soda concentrations lie between 10–15 wt%, and uranium is relatively high (Dussubieux *et al.* 2012: 320–321; Dussubieux and Gratuze 2013: 405).

While m-Na-Ca-Al glass plots similarly to m-Na-Al 1 glass on the previous PCA, the subtype can be distinguished from m-Na-Al 1 glass by undertaking a PCA using elements and compounds Na_2O, Al_2O_3, Rb, Zr, La, Hf, and Th (Dussubieux and Gratuze 2010: 252–254). Figure 15 visualizes the results of a PCA using a comparative dataset of m-Na-Al 1 and m-Na-Ca-Al glass artifacts from Phromthin Tai, Thailand (Carter *et al.* 2022) and UOJF0314. As seen in the figure, UOJF0314 plots more closely to m-Na-Ca-Al Phromthin Tai artifacts than with the control m-Na-Al 1 Phromthin Tai artifacts and is thus compositionally analogous to the m-Na-Ca-Al glass group (Figure 15).

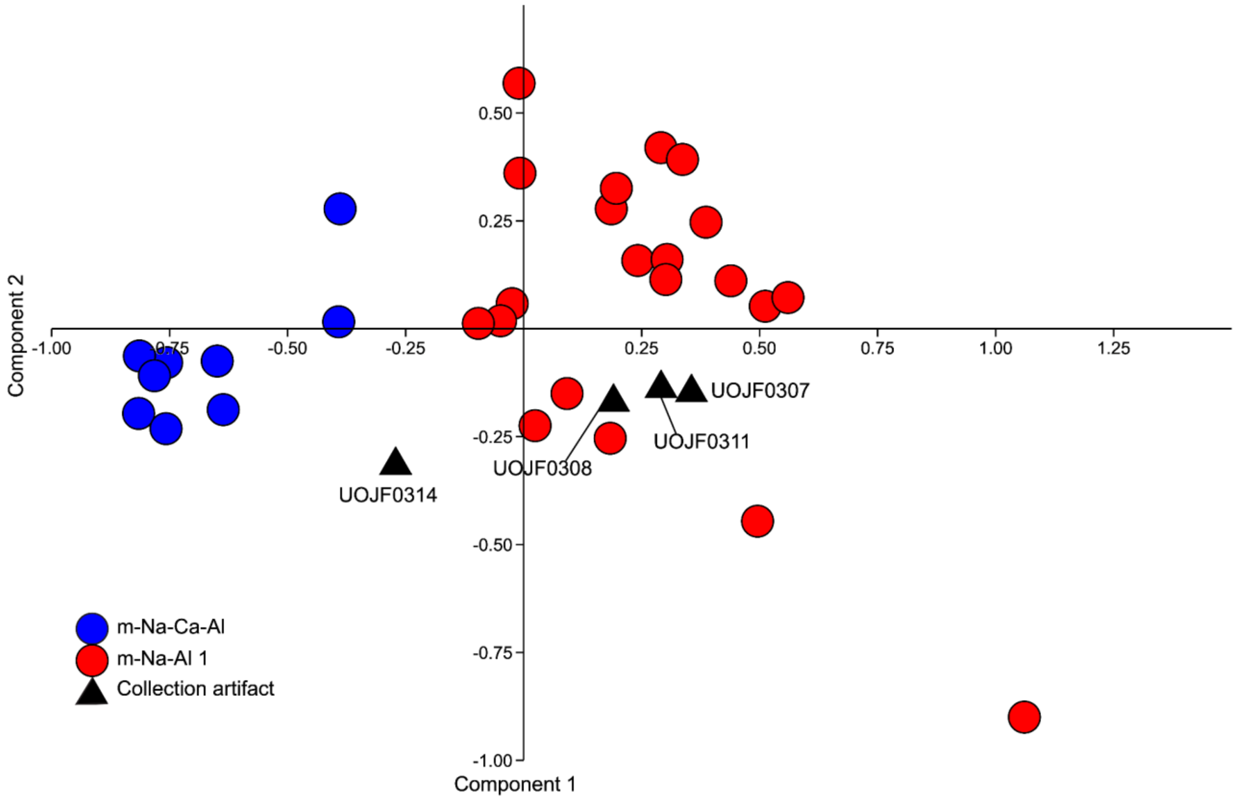

Figure 15. PCA differentiating between m-Na-Al 1 and m-Na-Ca-Al glass.

DISCUSSION

As elaborated upon earlier, when the collection artifacts were plotted against comparative compositional datasets of glass from Southeast and South Asia (Figures 13–15), these rare glass ornaments matched the compositions of previously studied glass ornaments (primarily beads) from known contexts in South and Southeast Asia. Indeed, the collection's two potash artifacts (UOJF0313 and UOJF0318) plot well within the known m-K-Ca-Al and m-K-Al comparative artifact compositions (Figure 13). Similarly, three collection mineral soda artifacts (UOJF0307, UOJF0308, and UOJF0311) plot well within the m-Na-Al 1 subtype, while UOJF0314 plots most closely to the m-Na-Ca-Al subtype (Figures 14 and 15).

Though this collection is looted, nullifying certain artifact contextualizations, we are able to situate these objects within *the most likely* exchange networks based on their glass compositions. We posit the early (late centuries BC) trade network that circulated potash glass objects along the South China Sea as a likely exchange network that brought this collection's potash ornaments to Phum Snay. However, as noted prior, the absence (or small quantities) of objects from this early exchange network throughout the Mekong Delta and at later inland Iron Age settlements (e.g., Phum Snay) evidences that this network was mainly littoral (Carter 2015: 748–749, 751), prompting the question of how communities in northwest Cambodia became connected with this South China Sea potash glass network.

Because of compositional similarities, the collection's high-alumina mineral soda glass likely arrived in northwest Cambodia via the later (first centuries AD) trade network that circulated mass-produced South Asian high-alumina mineral soda glass widely in both coastal and inland Southeast Asia. This influx of high-alumina soda glass is consistent with Song's (2010: 43) conclusion that potash glass circulation at Phum Snay, specifically, waned until completely halting around the third century AD.

It's notable that morphologically identical bangles in this collection have different glass recipes. UOJF0318 is moderate lime and alumina (m-K-Ca-Al) potash glass that's translucent light blue, and UOJF0314 is mineral soda glass with moderate amounts of alumina and lime (m-Na-Ca-Al) and is translucent dark blue. That shared morphology along with differing glass compositions evidences a single workshop working multiple glass types, a phenomenon seen at Khao Sam Kaeo and Khao Sek (Lankton *et al.* 2008; Dussubieux and Bellina 2018). Multiple glass types (potash, m-Na-Ca-Al) were likely worked at Phu Khao Thong as well, though the site's artisans do not appear to have made bangles (Dussubieux *et al.* 2012). These two bangles' shared morphology but distinct glass types may point toward South Asian production or a site in Southeast Asia with South Asian connections where this glass was imported and worked.

Another novel takeaway from this study includes the potash glass spiral ornament. As described earlier, this spiral/comma-shaped ornament type has been found elsewhere in Southeast Asia, and we believe this study is the first to report compositionally on this artifact type. This novel compositional data sparks questions about where and when the spiral ornament type was manufactured and the different morphological and compositional variants of this ornament type that may have been produced as well.

This work also demonstrates that earrings (in addition to beads) were made from m-Na-Al 1 glass, though these earring ornaments are rare and not as widely circulated as beads.

The diversity of glass types at Southeast Asian sites (e.g., Phum Snay) relates directly to trade networks and spheres of influence that operated as early as the Iron Age (Bellina 2018a: 1). Bellina (2018a: 1–2) delineates two interaction spheres in the Bay of Bengal and South China Sea that circulated, among other things, stone, glass, and metal goods. Furthermore, the Thai-Malay peninsula functioned as a both physical and cultural midpoint between the two spheres, yielding a zone that produced hybrid material culture (Bellina 2018a: 1). These hybrid products were most commonly traded litorally and, to a lesser extent, inland, mirroring the aforementioned South China Sea exchange network's mostly coastal nature (Bellina 2018a: 2). These spheres of influence functioned as the foundations of subsequent exchange networks, providing relational, temporal, and geographic scaffolding within which the South China Sea potash glass network and South Asian high-alumina mineral soda glass network make sense. Additionally, the likely barter/gift-giving nature of early exchange within these basins (Bellina and Glover 2004) fostered political relationships and power contextualized within Southeast Asian leaders' requisite "constant confirmation" of their political power and "complex system[s] of loyalty" both within their society and with adjacent political groups (Bellina 2018a: 3).

As a relevant example of such political power drawn from exchange, Carter (2013: 360) presents political elites in the Mekong Delta as a likely factor in controlling the circulation of high-alumina soda glass potentially along the delta's rivers to inland sites "that did not previously have regular access to the coastal potash glass bead trade network," such as Phum Snay. Carter (2013: 360, 417, 420) directly connects high-alumina soda glass's novel regional distribution with the Mekong Delta's gaining power during the early centuries AD by proposing that the Mekong Delta was a main supply of South Asian high-alumina soda glass for Southeast Asia, a status that elites in the Mekong Delta may have leveraged to increase their regional influence further inland. For example, Carter *et al*. (2021) describe Angkor Borei's assemblage including high-alumina soda glass produced in South Asia and note that glass's similarity to contemporaneous inland sites' glass assemblages, including Phum Snay. In sum, if these collection objects' provenience is indeed Phum Snay, this collection's rare m-Na-Al 1 and potash objects are consistent with Phum Snay having limited involvement with both the South China Sea exchange network and the later Mekong Interaction Sphere.

CONCLUSION

This work found that this collection's rare glass ornaments comprise both potash (m-K-Al and m-K-Ca-Al) and soda (m-Na-Al 1 and m-Na-Ca-Al) glass. Morphologically, the artifacts in study resemble known artifacts from Southeast Asia and specifically Phum Snay in some cases. These artifacts were most likely circulated within an early South China Sea potash glass exchange network and a later South Asian high-alumina mineral soda glass network, the latter of which may be associated with the expansion of a powerful polity located in the Mekong Delta that amplified trade circulation to inland areas such as Phum Snay. Of particular insight is this study's compositional analysis of the potash spiral ornament (the first analysis done on a spiral ornament) and the m-Na-Al 1 earrings. Also of note are morphologically identical bangles with differing glass compositions, suggesting a single workshop working varied glass types.

Finding rare objects such as those in this study in context would enable deeper understandings of rare glass ornament types and glass-working in Iron Age Southeast Asia in general. However, this work is a testament to the utility of studying unprovenienced archaeological materials as part of the repatriation process. In close, this work provides novel compositional and morphological analyses of rare, understudied glass ornaments and contextualizes such artifacts within known glass trade networks operating in Iron Age Southeast Asia. These rare artifacts ultimately expand existing understandings of Iron Age Southeast Asian glass exchange by demonstrating that glass circulation included non-bead ornaments constituting diverse glass types.

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