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The last natron glass production in middle Egypt in the 8th to 9th century CE

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ABSTRACT

Despite the fact that Egypt was a major producer of glass during the first millennium CE, the primary production locations of most Egyptian glass groups remain unknown. Identification of Egyptian glass is generally based on the assumption that its chemical composition differs from Levantine glass, which is relatively well known thanks to numerous archaeological remains. No production site in Egypt has been investigated to the same extent with regard to the properties of the glass. Raw glass chunks and furnace debris, as well as several finished objects collected at el-Ashmunein in Middle Egypt at the end of the 19th century and preserved in the Musée des Beaux-Arts in Limoges (France), were selected for analysis using LA-ICP-MS to address the perennial question of the primary production location of the last natron type glass of the ancient world. The analytical results provide evidence that Egypt 2 glass originated in el-Ashmunein, and contains manganese at varying concentrations that was added during primary production for the purpose of decolourisation. Comparison with published data of well-dated Egyptian glass weights further reveals a chronological evolution of the compositional properties of Egypt 2 glass with a decline in soda contents over time. Imported material in the form of plant-ash glass from Mesopotamia is evidence of the delayed introduction of plant ash based glass recipes to Egypt. Our study demonstrates that historical glass collections can be an important source of information to fill gaps in our knowledge of the history of glassmaking.

1. Introduction

It has been almost 40 years since [Bimson and Freestone \(1987\)](#) proposed the primary production of a high-calcium variant of mineral soda glass at el-Ashmunein in Middle Egypt. The study was based on the analysis of four fragments using energy dispersive scanning electron microscopy, and included a piece of waste glass recovered during the British Museum expedition in the 1980s. Since then, similar high-lime glass has emerged from other archaeological contexts in Egypt (group II of [Gratuze, 1988](#)); group 7 ([Foy et al., 2003a](#)); group N2-b ([Kato et al., 2009](#)) as well as Palestine (group N-3 ([Phelps et al., 2016](#))). A comprehensive study of early Islamic glass weights from Egypt determined the composition and chronology of the Egypt 2 group in more detail ([Schibille et al., 2019](#)), and these data have become an important point of reference for the classification and dating of early Islamic glass assemblages. Aside from the high calcium contents, Egypt 2 glass normally has low alumina and low strontium concentrations as well as high heavy element contents typical of natron glass produced in Egypt during the

first millennium CE ([Barfod et al., 2020](#); [Phelps et al., 2016](#)). It dates to the Abbasid period, more precisely from about 780 CE to the end of Abbasid rule in Egypt in 868 CE, making it the last natron-type glass of the ancient world ([Schibille et al., 2019](#)).

El-Ashmunein as the primary production site has been called into question due to uncertainties in the archaeological record at the time and the lack of suitable raw materials in the vicinity of the city ([Freestone et al., 2003](#)). It has been suggested that el-Ashmunein may have been merely a secondary glass workshop where raw glass of the Egypt 2 composition was processed rather than originally made ([Freestone et al., 2003](#)). However, the British Museum campaign uncovered archaeological remains which in hindsight, thanks to the discovery of large tank furnaces in Palestine and the Wadi Natrun in lower Egypt ([Brill, 1988](#); [Freestone, 2002](#); [Gorin-Rosen, 1995, 2000](#); [Gorin-Rosen, 2012](#); [Nenna, 2015, 2024](#); [Nenna et al., 2000](#); [Nenna et al., 2005](#); [Sa'id and Gorin-Rosen, 2022](#); [Tal et al., 2004](#)), are consistent with the remnants of furnaces for primary glass production. The glassmaking activities took place in the ancient Komasterion (assembly hall) on

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limestone flags that had been exposed to intense heat that penetrated deep into the underlying bricks, clearly indicating primary production rather than secondary processing (Bimson and Freestone, 1991). The only other remains of a primary production site in Middle Egypt from the early Islamic period are the ones recently discovered at Antinoopolis

(Sheikh Abada), but if the archaeological finds clearly show the relics of a tank furnace, the chemical analyses are not fully conclusive (Ballet and Guidotti, 2014; Silvano, 2015).

A unique opportunity presented itself to analyse raw glass chunks and furnace glass waste that were collected at el-Ashmunein by the

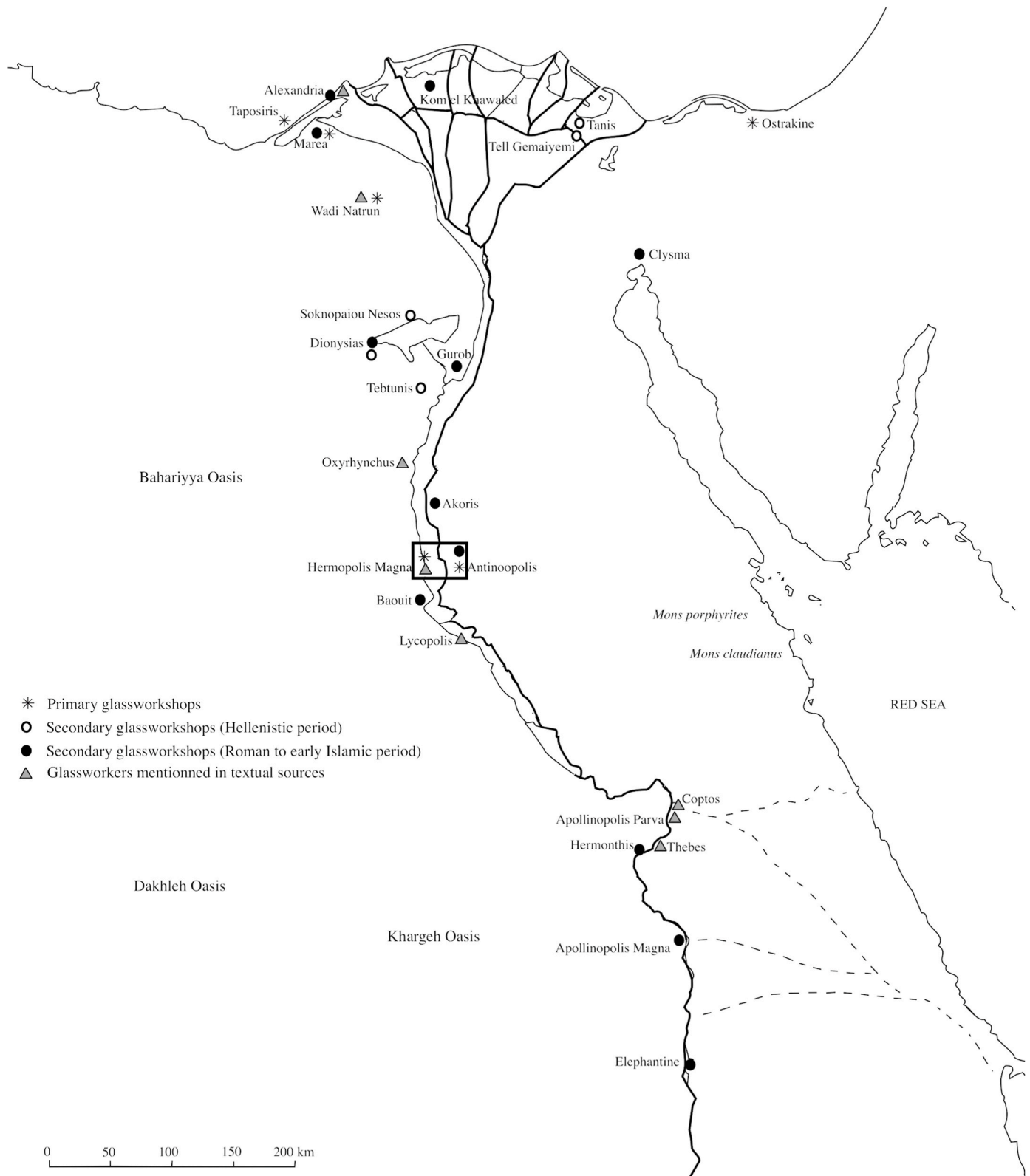


Fig. 1. Map of Egypt showing the locations of primary and secondary glass workshops, square highlights region around El-Ashmunein (see Fig. S1); © M.-D. Nenna.

French engineer Jean-André Périchon (1860-1929) at the end of the 19th century CE (Nenna, 2023). Périchon worked for 22 years (1885-1907) in the sugar factories of Rodah between El-Ashmunein and Antinoopolis in Middle Egypt (Fig. 1). During this time, he amassed almost 4000 archaeological objects, including about 200 glass artefacts, which he described in a recently discovered manuscript written in his own hand (1909) as « Les grosses pierres vitreuses irisées proviennent des fours à creuset d'une verrerie située à Achemouneim époque musulmane Xe siècle apr. J.-C. [...] Sous les califes musulmans du Xe siècle, il existait encore dans cette ville une verrerie d'où proviennent les fours de cubilot » (Tallet et al., 2023). Périchon may have had sufficient knowledge of the glass industry through his studies at the École des Arts et Métiers in Angers and/or visits to Flinders Petrie's excavations (1891-1892) at Tell Amarna, not far from where he lived. There, the remains of several glass factories as well as large quantities of discarded faience and glass were unearthed (Petrie, 1894). At the very least, Périchon visited Amarna, since he claimed that his terracotta moulds for amulets originated from there (Tallet et al., 2023). How Périchon was able to date the glass furnaces to the 10th century is less obvious. We know that he was involved in archaeological activities and in contact with numerous archaeologists in the region such as Georges Daressy and Albert Gayet (Duranteau, 2022), who discovered small Islamic flasks in Antinoopolis (Arveiller-Dulong, 2021) similar to the ones in Périchon's collection. The dating of the glassmaking remains and the bottles may therefore have come from discussions with Daressy, a specialist in historical geography, who consulted ancient sources in various languages and undertook numerous field trips, as evidenced by his *Atlas Archéologique* (Fig. S1; Daressy, 2019) and other publications (Perdu, 2017).

In this study, we analyse the material from the Périchon collection to gain new insights into the characteristics and the possible origins of the glass from el-Ashmunein. If it can be shown that the raw glass chunks and furnace glass from el-Ashmunein correspond to primary production waste of a homogenous composition, this may be proof of local raw glassmaking. As part of the data evaluation, our study revisits the analytical results of the Islamic glass weights with an Egypt 2 composition (Schibille et al., 2019). Comparison of the trace elements in the Périchon collection with published data of Egypt 2 glass corroborates a chronological shift of this glass composition, which appears to apply also to the use of manganese for decolourisation.

1.1. History of El-Ashmunein

El-Ashmunein is located 300 km south of Cairo between the Bahr Youssef canal and the Nile, today 2.5 km from the Nile (Fig. 1, S1). In Pharaonic times it was known as Khemenu, the Greeks called it Hermopolis (city of Hermes), the Romans Hermopolis Magna. It was the capital of the Hermopolite nome, an independent geographical unit specific to Middle Egypt. The valley, about 20 km wide, is very fertile thanks to the Bahr Youssef canal, especially along the western bank extending to the foothills of the Libyan Mountains, while the opposite bank is often reduced to a narrow strip between the Nile and the Arabian cliff (Drew-Bear, 1979, 1981). On the east bank of the Nile, at roughly the same latitude as Hermopolis, emperor Hadrian founded the city of Antinoopolis in 130 CE as the cult centre for the deified Antinous and the starting point of the via Hadriana that led from the Nile to the Arabian desert and the ports on the Red Sea. In late antiquity, el-Ashmunein and Antinoopolis were important monastic centres and maintained close trade relations (Bunbury and Malouta, 2012; Malouta, 2010, 2016). A fiscal codex from Hermopolis from the eve of the Islamic conquest (618/19 or 633/34 AD) shows how strongly Christianity had shaped the city and its region since the 4th century (Gascou, 1994; Gascou, 2019). Between 725 and 830, however, the Christian community was gradually reduced to a minority, monasteries were abandoned, fell into disrepair or were fortified (Martin, 1987). Arabic written sources offer little information about the city and its topography at the beginning of the Islamic period (Grohmann, 1938; Legendre, 2014b), but they confirm that

the city retained some importance until at least the end of the 11th century CE (Björnesjö, 1998; Legendre, 2014a, 2014b).

Hermopolis and Antinoopolis were repeatedly looted since the time of Saladin; building materials and columns were moved to other cities in the region and to Cairo for the construction of city walls and mosques (Björnesjö, 1998). Ancient building materials of el-Ashmunein were also used for the construction of the Rodah sugar factory in 1818 (Duranteau, 2022). The main reason for the destruction of ancient remains, however, was the search for nitrogen-rich soil, which involved laying two narrow-gauge railways into the hills of Hermopolis no later than 1884 and used until the 1930s (Bailey, 1999; Breccia, 1905), and the manufacture of lime and saltpetre described by Jomard, a member of the Expédition d'Égypte (Jomard, 1818). Hence, when Périchon visited el-Ashmunein from 1887, it was already a vast field of plundered ruins, from which few architectural elements emerged.

Three major archaeological expeditions were carried out: from 1929 to 1939 on behalf of the Pelizaeus Museum in Hildesheim by G. Roeder, during the Second World War by the Egypt Antiquities Service and the University of Alexandria, and in the 1980s by the British Museum under the direction of J. Spencer (Bernard, 1999). These excavations took place after the almost complete demolition of the upper levels, and they uncovered architectural remains from the early Islamic period. However, apart from brief mentions (Roeder, 1959; Bailey, 1991a, 1991b), we only have a vague idea of the development of the city from the Arab conquest to the Ottoman period. Surveys in the 1990s, focusing on the mounds above the site, identified architectural remains, including Fatimid-era residences (Björnesjö, 1998). Waste heaps from pottery workshops were found in the south-east next to the Basilica (Ballet et al., 1991; Ballet, 2000). El-Ashmunein and Antinoopolis were major centres of amphora and pottery production during the Byzantine and early Islamic periods (Ballet and Guidotti, 2014). The production and trade of AE 7 amphorae is documented until the end of the 9th or the beginning of the 10th century (Dixneuf, 2011), while culinary ware and big carinated bowls were produced and traded throughout Egypt until the 10th/11th century (Ballet and Guidotti, 2014). No remains of glass workshops were discovered during the surveys of el-Ashmunein, but evidence of a tank furnace for glassmaking has come to light at Antinoopolis (Fig. S2), associated with early Islamic glazed pottery (Ballet and Guidotti, 2014; Silvano, 2015).

1.2. Sampling the Périchon collection

The collection is largely preserved at the Musée des Beaux-Arts in Limoges, where a recent exhibition enabled us to view and select the samples for the present study (Tallet et al., 2023). A total of 28 samples were chosen for analysis (Supplementary Table S1), including 13 raw glass chunks with some calcareous material and/or unmolten batch adhering to them, 7 raw glass fragments with no furnace material attached, 6 vessel fragments, one miniature bottle and one large fragment that may have been a commodity weight (Fig. 2). The main selection criterion was to include all possible indicators related to glass working, as well as vessels that could be chronologically attributed to the early Islamic tradition such as vessels with tonged decorations and elongated cobalt-blue flasks that are characteristic of the 9th and 10th centuries. Three cobalt blue samples were included, since the cobalt pigment provides an additional temporal and geographical discriminator. These objects serve to examine the variability of the glass in el-Ashmunein and to ascertain whether the composition of the raw glass matches that of the objects from the early Islamic period.

2. Analytical methods

The chemical composition of the glass samples was determined by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Analysis was done on a Thermo Fisher Scientific ELEMENT XR mass spectrometer combined with a Resonetics M50E excimer 193 nm

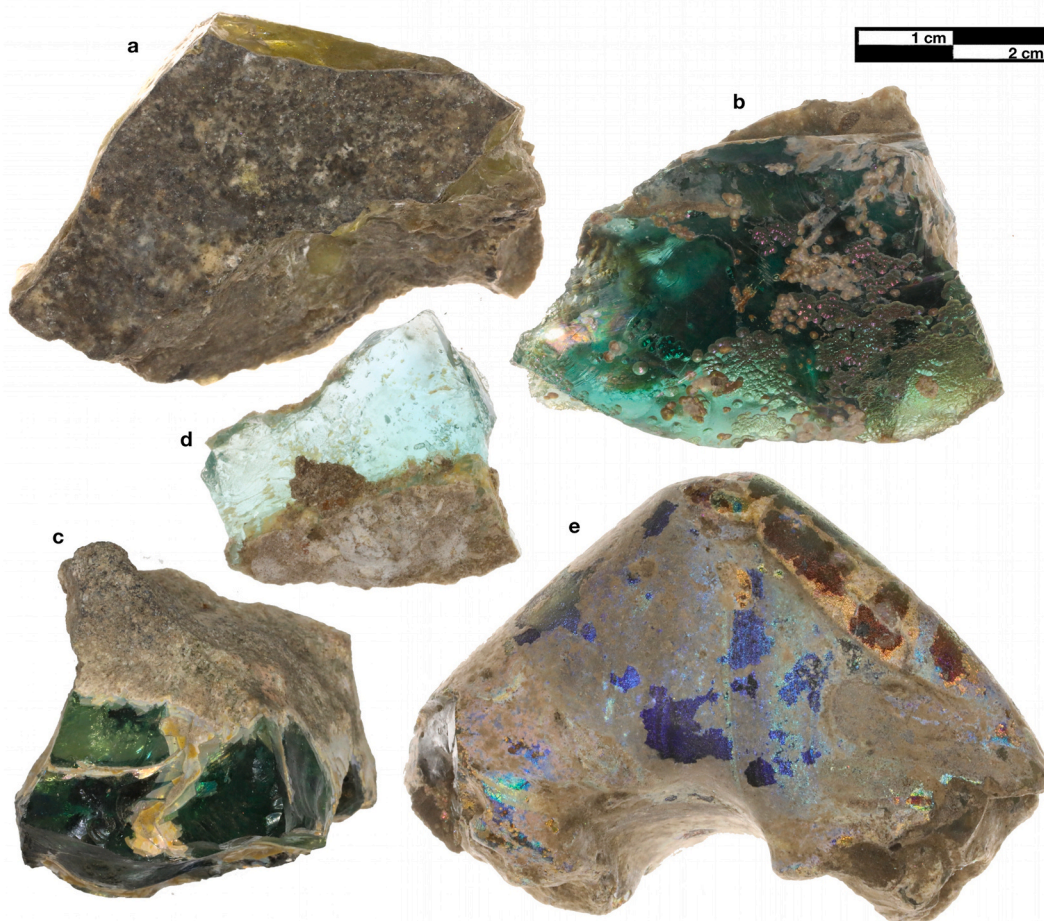


Fig. 2. Selection of samples analysed in this study. (a) Greenish glass chunk E.102a_002 with calcareous material attached to the underside; (b) bluish-green glass chunk E.102a_019 with calcareous material and fragment of limestone; (c) dark green glass chunk E.102a_020 with calcareous material attached to the sides and underside; (d) bluish glass chunk E.102a_021 partially showing calcareous concretions; (e) commodity weight E.102a_030 showing considerable alterations and iridescence on the surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

laser at IRAMAT-CEB, Orléans (France). Each sample was analysed at least twice and up to five times if the sample was not homogenous, using single spot mode with a beam size of 100 μm , 5 mJ energy and a repetition rate of 10 Hz. A pre-ablation time of 15–20 s depending on the surface condition of the samples was followed by approximately 27 s of acquisition, resulting in 9 mass scans for each of the 58 analysed isotopes. ^{28}Si was used as an internal standard, while five reference glasses (NIST610, Corning B, C, D and APL1) were used to calculate the response coefficients for each element and to obtain fully quantitative data (Gratuze, 2016; Schibille et al., 2024). The repeated analysis of Corning A and NIST612 provided accuracies within 5% for all major elements except for Al, P, Cl and Ca in the Corning A standard, and within 8% for trace elements except for Zn, Nb, Mo, Sn, Ta, W and Pb in NIST612 (Jochum et al., 2011). Reproducibility was well within 5% for most elements (Table S2).

3. Results

3.1. Classification of the base glass

All analysed samples from the Périchon collection are soda-lime-silica glass and, except for two cobalt blue fragments (E.039, E.102c012), have low MgO and K₂O concentrations (<1 wt%), indicating the use of mineral soda as the fluxing agent (Table S2). Natron glass is commonly classified into regional and chronological production groups based on the accessory minerals contained in the glassmaking

sands (Foy et al., 2003b; Freestone et al., 2000; Schibille, 2022). Aluminium, calcium, titanium, zirconium, as well as the rare earth elements (REEs) have proven useful to distinguish different silica sources and regional origins (Freestone, 2021; Gratuze and Foy, 2012; Schibille et al., 2017). The natron glass from the Périchon collection is characterised by a silica source relatively low in alumina (1.8–2.8 wt%), strontium (<200 ppm) and REEs, but high in lime (up to 11 wt%), titanium (1200–2000 ppm) and zirconium (120–300 ppm). The overall compositional features of the Périchon samples are therefore similar to Egypt 2 glass (Table 1) identified in Islamic glass weights from Egypt (Schibille et al., 2019) and vessel fragments found in Palestine that typically date to the 8th and 9th centuries (Phelps et al., 2016). Note that one sample (E.102b027) was excluded as it has exceptionally high levels of heavy elements such as Zr, Hf and Th (Table S2).

A comparison of the Al₂O₃/SiO₂ and TiO₂/Al₂O₃ ratios confirms the chemical similarities between the Périchon samples and glass of the Egypt 2 type, while some differences exist (Fig. 3a). The Al₂O₃/SiO₂ ratios of the Périchon assemblage are within the range of the Islamic glass weights (Schibille et al., 2019) and Egypt 2 glass from Palestine (Phelps et al., 2016). However, about half of the samples have higher TiO₂/Al₂O₃ ratios due to somewhat higher titanium and lower alumina contents. The samples with elevated TiO₂/Al₂O₃ ratios tend to also have lower lime concentrations (Table S2). There is no obvious link between object type and variations in composition and/or homogeneity of the glass matrix. For several raw glass chunks with high titanium and low lime levels (e.g. E.102a007; E.102a012) several points were measured

Table 1
Mean concentrations and standard deviations (σ) of major, minor and selected trace elements in the Périchon samples as measured by LA-ICP-MS (separated by Mn content), compared to published data of Egypt 2 divided into two chronological groups (Schibille et al., 2019).

	wt%										ppm									
	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	Cl	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	Sr	Zr	Ba	La	Nd	Eu	Gd	Tb	Hf
Périchon no Mn (n=10)	13.9	0.56	2.36	70.9	0.18	1.06	0.30	9.39	0.26	0.02	0.93	160	165	139	6.84	6.23	0.33	1.26	0.18	3.79
σ	0.9	0.10	0.25	1.2	0.14	0.07	0.06	0.73	0.03	0.00	0.07	17	21	18	0.47	0.35	0.03	0.08	0.01	0.45
Périchon high Mn (n=9)	14.2	0.51	2.07	70.3	0.24	1.12	0.35	8.64	0.28	1.16	0.97	151	208	199	6.86	6.38	0.33	1.35	0.20	4.74
σ	0.6	0.11	0.19	1.1	0.21	0.11	0.09	1.15	0.05	0.26	0.15	18	63	28	0.46	0.52	0.02	0.21	0.02	1.38
Egypt 2 (< 815 CE; n=12)	16.5	0.47	2.00	69.7	0.10	1.08	0.33	8.51	0.20	0.05	0.84	139	120	119	5.93	5.40	0.28	1.06	0.16	2.72
σ	1.0	0.09	0.30	1.8	0.05	0.13	0.08	1.26	0.02	0.08	0.30	16	24	18	0.31	0.32	0.02	0.12	0.01	0.52
Egypt 2 (> 815 CE; n=24)	13.4	0.70	2.52	70.1	0.11	1.04	0.51	9.57	0.27	0.44	1.18	188	181	183	7.32	6.57	0.33	1.18	0.19	3.99
σ	0.5	0.15	0.20	1.3	0.04	0.09	0.24	0.52	0.03	0.46	0.31	20	26	35	0.50	0.42	0.02	0.11	0.01	0.56

(≤ 5) to trace possible contaminations that may have been caused by a reaction of the silica melt with the calcareous surface layer (Fig. S3). However, the composition of the bulk glass of the samples and the glass close to the lime crust on the surface was found to be indistinguishable. This suggests that the differences in the accessory elements such as titanium and lime are due to variations in the silica source and different proportions of feldspars, limestone and heavy minerals and not to contamination through the furnace walls or the ground rich in lime. Since no sample preparation was possible, we could not investigate a possible interaction between the glass and the furnace wall material any further.

The natron glass from the Périchon collection has very low strontium relative to calcium, which is typical of the Egypt 2 compositional group (Fig. 3c). The low Sr/Ca ratios can be attributed to limestone as the source of calcium rather than shell from coastal sands (Freestone et al., 2003). Like the Islamic glass weights and vessels, the Périchon samples display a Zr to Ti correlation that is clearly distinct from earlier Egyptian glass groups such as Egypt 1 (Fig. 3b). These data confirm that the natron glass from the Périchon collection corresponds to the Egypt 2 composition and that a common origin of the raw glass can therefore be assumed.

The soda concentrations of the Périchon samples show little variation and are similar for raw glass chunks and vessel fragments (12.5–15.5 wt% Na₂O), except for a cobalt blue sample (E.102c011) with 17.5 wt% Na₂O (Table S2). These concentrations are relatively low for Egyptian glass and corresponds more to a later subgroup of Egypt 2, namely the glass weights that were produced after 815 CE and that are characterised by decreasing soda contents (Schibille et al., 2019). This compositional distinction is also reflected in the higher trace element patterns associated with the silica source (Fig. 4). The Périchon glass thus tends towards the later Egypt 2 subtype, both in terms of soda content and silica-related trace elements. That said, the two groups are not identical. The glass weights are slightly richer in all trace elements, but for an unexplained negative Gd anomaly not visible in the Périchon samples (Fig. 4). Finally, two samples show some unusual compositional features. A fragment of a bowl with toothed line decoration (E.102b027) has higher Ti and Zr values compared to all other Egypt 2 data, yet it appears to lie on the same regression line and may therefore be the result of some mineral agglomeration in the same sand source (Fig. 3b). A flat piece of glass (E.102a026), the purpose of which is not entirely clear, has an unusually low chlorine content (0.3 wt%). The loss of Cl could be attributed to higher temperatures or repeated exposure to heat, and may have been aided by the thinness of the fragment.

Two cobalt blue fragments, a bottle neck (E.102c012) and a convex bottle base (E.039) were made using soda-rich ashes of halophytic plants with relatively high soda (12–13 wt%), moderate magnesia (2.6–4 wt%), potash (~2.2 wt%) and lime (5.6–6.6 wt%) concentrations (Table S2). Elevated Cr/La ratios and high lithium contents suggest a Mesopotamian origin for these plant ash glasses (Schibille, 2022). The morphological features indicate that the two fragments belonged to an extremely widespread type of elongated, cylindrical bottle with rounded base and thin neck, made of very thin, blue glass (Foy, 2020).

3.2. Additives – manganese and cobalt

The manganese concentrations in the Périchon glass range over two orders of magnitude, from about 140 ppm to almost 14000 ppm, potentially indicating a scenario similar to that proposed for 4th-century glassmaking at Jalame in Palestine, where uneven distribution of manganese in a large primary furnace led to considerable colour variations in the same melt (Freestone et al., 2023). The final colour of the glass depends on the combination of several factors, including the total amount of manganese and its redox state relative to iron. Following the example of the Jalame study, we divided our dataset into three groups according to the manganese content, in order to examine the extent to which the manganese additive had an effect on the base glass

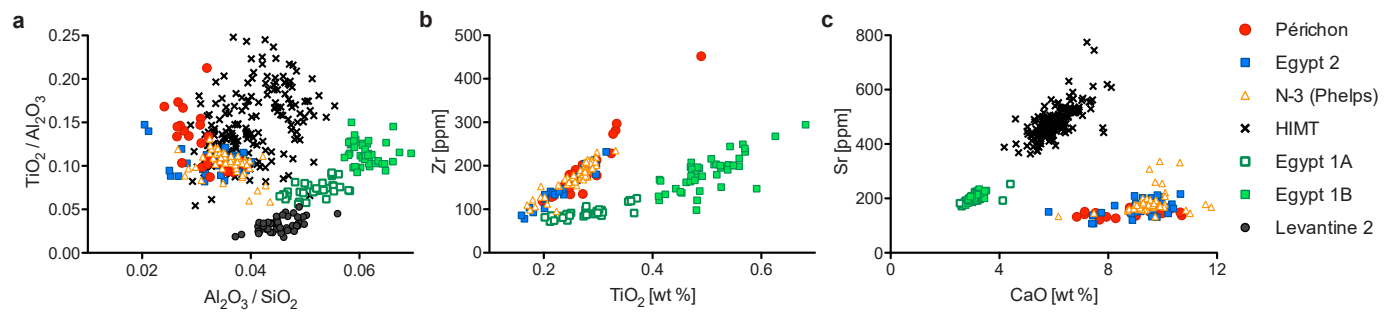


Fig. 3. Base glass characteristics of the Périchon glass compared to published data of Islamic glass weights from Egypt (Schibille et al., 2019) and N-3 samples from Palestine (Phelps et al., 2016) as well as some HIMT glass for comparison (Ceglia et al., 2019; De Juan Ares et al., 2019; Foster and Jackson, 2009; Freestone et al., 2018); (a) Al_2O_3/SiO_2 versus TiO_2/Al_2O_3 ratios associate the Périchon samples with Egypt 2; (b) TiO_2 and Zr show different correlations in the Egypt 2 samples compared to Egypt 1A and Egypt 1B; (c) the Périchon glass along with all Egypt 2 samples have low Sr despite high calcium contents.

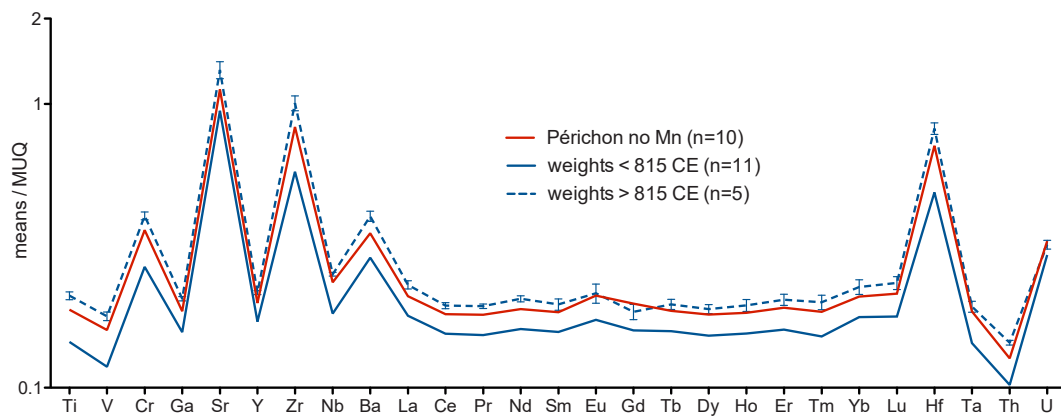


Fig. 4. Trace element patterns of the Périchon glass without MnO compared to data of Islamic glass weights from Egypt divided into two chronologically distinct subtypes (Schibille et al., 2019); data were normalised to the upper continental crust according to (Kamber et al., 2005).

composition and whether glass with low manganese concentrations is closer to other glass of the Egypt 2 type.

One group has manganese at background levels ($Mn < 200$ ppm), probably related to the sand source. In a second group, the manganese contents (350-1500 ppm) exceed the natural impurity levels in the silica source but are too low to have an active (de-)colouring effect. Finally, a high manganese group (0.8-1.8 wt%) was defined, in which Mn was deliberate added for the purpose of (de-)colouring. A comparison of the trace element profiles of the three groups shows that elements normally associated with the silica source may indeed have been affected by the Mn-containing additive (Fig. 5). Heavy elements such as Ga, Zr, Nb, Hf,

Th, U, as well as the heavier REEs seem to be slightly enriched in glass containing manganese, even though the trends of the low Mn and the high Mn glass appear contradictory in places (e.g. Ga, Zr, Hf). Other elements visibly affected by the addition of manganese include Co, Ni, Cu, Zn, As, Mo, Cd, Ba and W (Table S2). The high Mn group shows a strong positive correlation between Mn and Co, Ni, Zn, Mo, Ba and W.

Even within individual samples, there is evidence of a significant gradient of manganese concentrations. For example, we identified an undissolved Mn-rich particle in sample E.102a 030 that bled into the surrounding glass. Multiple analyses revealed a gradient of manganese concentrations from 0.02 to 1.77 wt% on a scale of a few millimetres

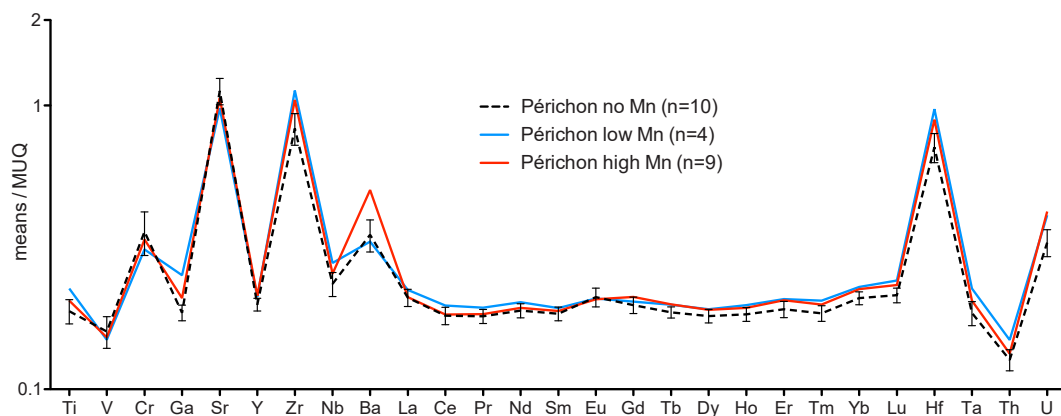


Fig. 5. Trace elements of the Périchon glass normalised to the upper continental crust (Kamber et al., 2005) separated on the basis of Mn concentrations, demonstrating the influence of the Mn-additive on the base glass composition.

from the aggregate (Fig. S4). It should be noted that this sample, possibly the fragment of a large commodity weight, has a heterogeneous and stratified morphology and is an excellent example of inadequate mixing. Whether the inclusion is the result of secondary processing rather than a primary production residue is impossible to say. Raw glass chunks from the Périchon collection provide evidence that manganese was added during primary production and that it was often unevenly distributed in the glass matrix. Several analyses of the same raw glass fragments show that Mn concentrations are not uniform (e.g. 0.14–0.49 wt% in sample E.102a 007), even if the range is nowhere as extreme as when Mn-rich particles are present.

Three natron-type glasses and the two plant ash samples are cobalt blue (Table S2). Zn is highly elevated in all five samples, but strongly correlated with cobalt in only two samples (E.102a 016, E.102c011), while the cobalt signature of the miniature bottle with a natron glass signature (E.069g) points to a copper-rich variant (Table S2). The two plant ash fragments were coloured by a cobalt colourant high in nickel (Co/Ni < 10). This means the glass finds from the Périchon collection contain three of the four different cobalt pigments that have been identified in early Islamic glass from the ninth to twelfth centuries CE (Schibille, 2026).

4. Discussion

4.1. Egypt 2 glass and its production location

The similarity of the Périchon glass with the data of Egyptian glass weights (Schibille et al., 2019) and finds from Palestine (Phelps et al., 2016) confirms that it belongs to the so-called Egypt 2 primary production group. This applies not only to the raw glass, but also to all the natron-type vessels collected by Périchon and analysed in this study. Our data from el-Ashmunein show a relatively low soda content, close in composition to the later glass weights (>815 CE) (Schibille et al., 2019). The differences in soda content reflect changing recipes and different proportions of the two main ingredients silica and natron. Compared to the earlier glass weights, the Périchon samples show a reduction of about 15% in soda (Table S2). Concurrently, the silica-related elements increase over time but not to the same degree. A difference between the post-8th-century glass weights and the Périchon samples relates to the alumina levels and silica-related trace and rare earth elements, which are on average lower in the raw glass from el-Ashmunein (Table 1). What we seem to see in the combined datasets of the Egypt 2 weights and the Périchon assemblage is a gradual increase in the fraction of accessory minerals in relation to the quartz content of the silica source. This difference in composition does not necessarily mean a change in the location of primary production or the sand source. Silica sources are subject to changes in exploitation patterns and natural erosion processes affecting the mineral makeup and grain size that in turn can have an effect on glass processing losses. The clear overlap between the different datasets and the seemingly continuous and constant shift in composition, the decrease in soda and the increase in mineral impurities, and stable titanium to zirconium ratios, strongly support the use of the same silica sources and glassmaking practices that underwent gradual changes.

Based on the chemical composition, it can be argued that el-Ashmunein was one of the places of manufacture of the Egypt 2 natron glass group. Archaeological evidence attests industrial activities at el-Ashmunein involving high temperature processes that led to the calcination of the limestone floor interspersed with glass waste (Bimson and Freestone, 1987). In retrospect, the remains discovered during the British Museum expedition in the 1980s appear to be consistent with tank furnaces used for the production of raw glass. The glass collected by Périchon matches these observations in that it includes raw glass chunks with lime mortar and limestone attached that was probably part of the furnace structure (Table S1). In one case (E.103a023) the glass is sandwiched between two layers of lime mortar. The presence of

abundant, fairly large chunks of raw glass with adhering furnace material is proof of local primary production, despite the fact that similar materials were also occasionally traded (Benzonelli et al., 2024; Natan et al., 2021). The consistent analytical data and compositional homogeneity of the glass assemblage as a whole support this interpretation. Apart from two vessels made from plant ash glass, all the analysed samples are Egypt 2, with only minor variations that can be attributed to the presence or absence of manganese. The extent to which the material collected by Périchon is representative of the archaeo-vitreous record at el-Ashmunein is of course debatable. We know nothing about Périchon's sampling strategy, but we can assume a certain degree of chance, depending on the probability of survival and access to the samples in the 19th century. In this sense, the sampling may be regarded as relatively unbiased and representative of the glass in circulation in el-Ashmunein at a given time, bearing in mind that the archaeological record is always incomplete. Interestingly, the two plant ash glass vessels are contemporary to the natron glass of Egypt 2. It would then appear that the analysed glass from the Périchon collection consists exclusively of ninth- to tenth-century material. None of the finds examined appears to originate from a later period. This is consistent with the fact that el-Ashmunein was an important centre for pottery production until the ninth or possibly tenth century, but not much later.

It has been argued that the low strontium contents and distinctive Sr isotope ratios of the glass from el-Ashmunein indicates the use of an inland sand that contained tertiary limestone instead of shell as a source of calcium (Freestone et al., 2003). Even though there are no outcrops of Oligocene limestone in the immediate surroundings of el-Ashmunein that would result in such a distinctive strontium signature (Freestone et al., 2003), some sand and Nile mud samples collected at Amarna about 25 km to the south have relatively low Sr/CaO ratios similar to those of Egypt 2 glass (Brill and Stapleton, 2012). This is in stark contrast to all other silica sources and, in fact, the LBA glass from Amarna analysed by Robert Brill that typically exhibit much higher Sr/CaO ratios (Brill, 1999). Only one sand sample from Cairo shows comparably low Sr/CaO ratios (Degryse, 2014). Unfortunately, the analyses carried out on some fragments recovered from the tank furnace at Antinoopolis are inconclusive (Silvano, 2015) and do not allow a direct comparison with Egypt 2 glass. Given the chronological context of the finds from Antinoopolis and el-Ashmunein, as well as the composition of the raw blocks from the Périchon collection, it is therefore reasonable to assume that primary glass production took place in el-Ashmunein during the early Islamic period, and that the glass produced was of the Egypt 2 type, the last natron glass made until the late 9th century CE.

Our findings call for a reassessment of the role of Middle Egypt in ancient glass production. Textual sources are abundant compared to the rest of Egypt and support a continuous glassmaking tradition since Roman times. For example, two glassworkers from Coptos were employed in 253 CE in glazing several monuments of Panopolis, a certain Aurelios Loukas, alias Potamon, appears as a glassworker in Lykopolis in 287 CE, and the existence of a glassworkers' guild in Oxyrhynchus in the early 4th century is well documented by papyri dated to 315 CE, 317 CE (price of the glass) and 326 CE (glazing of monuments). In el-Ashmunein itself, a glassworker is mentioned in the late 4th century (Nenna, 2021 and references therein). In 888 CE, al-Ḥusayn b. Šālih al-zuġġāġ (the glassworker) is listed in a legal document along with Qāma bt. Idrīs, both residents of the city of Ašmūn (Grohmann, 1934) (*P.Cair.Arab.* I 52). The terms, *ὑελοουργός* and *ὑαλῆς* do not indicate whether the individual was involved in primary or secondary production, but the presence of a *κοινὸν τῶν ὑελοουργῶν* in Oxyrhynchus clearly reflects a concentration of glassworkers, if not glassmakers in Middle Egypt. The site of Oxyrhynchus has a similar history to el-Ashmunein, both in terms of its longevity and looting (Björnesjö, 1998). Remains from the early Islamic period were excavated and attributed to the 11th/12th century (Breccia, 1933). Glass vessels and small flasks that can now be dated to the 9th/10th century were unearthed in one building, some resembling those in the Périchon

collection (Breccia, 1933). The strict distinction between primary and secondary workshops may not necessarily apply, as the example of Jalame shows, where both activities have been confirmed. This could also be the case in Antinoopolis where circular kilns were attributed to secondary workshops (Silvano, 2015), as well as in el-Ashmunein, where defective pieces such as E.102a018 are attested.

4.2. The glass vessels

Five of the seven glass vessels have an Egypt 2 composition. Three fragments of cylindrical cups with tonged decoration (E.102b_027-029) belong to a widespread type of drinking vessel that replaced Byzantine stemmed goblets in the Mediterranean region in the late 8th/9th century. They reflect a technological change with the use of a new tool (tongs) for producing geometric or vegetal decorations as well as a cultural shift in dining traditions, from small individual to large cups (Keller, 2014). The greenish, yellowish and bluish vessels were all made from Egypt 2 glass, similar to objects from Fustat (Foy et al., 2003a) and from the Sinai, where numerous similarly decorated cylindrical cups of a Egypt 2 composition were unearthed in 9th-century Raya (Kato et al., 2009). The two miniature bottles (E.069g and E.102c 011) were selected for their distinctive deep blue colour. Their size and form reflect a miniaturisation compared to late antiquity. These types of bottles were mass-produced and form the bulk of the Périchon collection, again with parallels in Fustat (Scalon and Pinder-Wilson, 2001).

Evidence for glass imports to el-Ashmunein comes in the form of the remaining two cobalt blue plant ash fragments, which belong to a very distinct type of thin, cylindrical glass bottles found across the Islamic world. They are known from Şabra al-Manşūriya near Kairouan in Tunisia (Foy, 2020), several sites in Egypt (Foy, 2001; Shindo, 2003) and Palestine (Phelps, 2018), Samarra in Iraq (Schibille et al., 2018), and Nishapur in eastern Iran (Kröger, 1995). To date, the earliest examples of these bottles come from 9th-century Samarra, and have been in circulation particularly in the 10th century CE (Foy, 2020). The bottles appear to have been mass produced as containers for a specific purpose and were usually imported as finished products. They consequently often stand out from the rest of an assemblage as they differ in composition. The vast majority of cobalt blue bottles for which we have reliable trace element data (Samarra, Palestine, el-Ashmunein), show an almost perfect positive correlation between aluminium, titanium and zirconium (Fig. S5), suggesting related silica sources and by extension a primary production in Mesopotamia (Schibille, 2022). Different cobalt pigments have been used to colour these bottles. While the flasks from Samarra were all coloured using a copper-rich cobalt colourant (Schibille, 2026), the samples from Palestine (Phelps, 2018) show either a copper-rich or nickel-rich cobalt signature. It is significant that the cobalt pigment rich in nickel used in Islamic glass dates to the 10th century and later, while copper-rich and zinc-rich variants were already used as early as the 9th century (Schibille, 2026). If we take this as a chronological marker, the Egypt 2 glasses from el-Ashmunein, two of which have elevated zinc contents, possibly predate the imported cobalt blue plant ash glass objects, which were coloured with a nickel-containing cobalt pigment.

5. Conclusion

Historical glass collections, even if they come from unstratified and often unspecific contexts, can offer valuable insights into the history of glassmaking. This is particularly relevant in the case of Egyptian glass given the export ban on archaeological materials from Egypt. Based on detailed chemical characterisation of a heritage collection from the Musée des Beaux-Arts in Limoges, el-Ashmunein can be identified as a primary production site of Egypt 2 glass, which played a major role in glassmaking in Middle Egypt in the 8th/9th century CE, with Antinoopolis perhaps being another centre. Unlike the somewhat older Egypt 1 glass, Egypt 2 has been found in medieval archaeological contexts as far afield as Umayyad Spain (De Juan Ares and Schibille, 2017)

and Viking-age Denmark (Sode et al., 2022) albeit in small numbers. Why this natron glass group appeared during the Abbasid period and became a trade commodity is not altogether clear. The natron-glass industry was in decline in Egypt from the 9th century, in favour of plant-ash glassmaking. There is evidence that soda-rich plant-ash glass travelled between regions, possibly in the form of specialised finished objects, even to places with a long-standing tradition of local natron-type glassmaking, the reasons of for this remain to be seen.

CRediT authorship contribution statement

Nadine Schibille: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marie-Dominique Nenna:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization.

Data statement

All data generated within this study are made available in the published article and its supplementary material.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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