

Plant-ash glass in Natronland: A review of the use of plant-based fluxes in glassmaking from the 1st to the 9th century CE in Europe and the Mediterranean basin

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ABSTRACT

This article examines available evidence for the use of plant ashes in glassmaking in the Mediterranean basin and Europe from the 1st to the 8th-9th century CE. During this period, glassmaking in these regions was overwhelmingly dominated by mineral fluxes, primarily natron, but the chemical composition of some glasses found in secure archaeological contexts suggests the use of plant ashes in these glasses, which are, on the other hand, compositionally distinct from glass made in regions where plant ash was used as the standard flux, for instance east of the Euphrates. The chemical characteristics of these glasses are examined, and different criteria are presented to aid in their identification. The chemical features are also interrogated to suggest possible silica and alkali sources and to determine possible similarities and differences in raw materials supply vis-à-vis natron glass. The archaeological and chemical evidence is brought together to try to define the technological, economic, and institutional implications of a possible glassmaking industry using plant ash, whose production parameters differ from those mobilised by the natron glass industry, in the periphery of the Roman world.

1. Introduction

This paper examines available evidence for the use of plant-ash fluxes in glassmaking in the Mediterranean basin and the European continent from the turn of the Common Era to the period straddling Late Antiquity and the Early Middle Ages. We refer to this geographical and chronological frame as 'Natronland', to emphasise the fact that glassmaking in this period and region was overwhelmingly dominated by the use of mineral-based fluxes, soda-rich salts typically referred to as natron (see [Shortland, 2004](#)).

Some sections of the paper revolve around chemical analysis, which is our only means to more-or-less reliably distinguishing between glasses made with mineral- and plant-based fluxes. For the most part, we rely on already published material, although some unpublished samples will also be reported. Our aim, however, goes further than to simply collect and examine chemical data and outline identification criteria. Primarily, we present some ideas concerning the use of plant ashes in a mineral flux-dominated industry and its potential role in the emergence of an industry of plant-ash glass – as distinct from a glass industry *with* plant ash – during the Middle Ages, as well as the potential social, economic, and

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institutional contexts and implications of these technological phenomena.

The use of plant ash in glassmaking had a millennia-long history before the Common Era, for instance during the Bronze Age in the Middle East and Egypt, and these fluxes remained in use east of the Euphrates throughout the Roman and Late Roman periods, when natron-based glasses dominated further west (Smith, 1963; Simpson, 2014; Kaparou and Oikonomou, 2022). Similarly, plant-ash based glassmaking becomes the norm across Europe and the Mediterranean basin from the end of the 1st millennium CE onwards, with potash-rich ashes in Europe and soda-rich ashes around the Mediterranean. Here, therefore, we focus on the intervening period between these two.

One of the reasons that motivates this paper is the reporting in recent years of a comparably large number of late antique glasses (6th–7th century) whose chemical composition could suggest the use of a plant-ash flux. In any case, the special prominence of these glasses in some 6th- and 7th-century assemblages (assuming this is not only to do with matters of archaeological visibility), must not obscure the fact that a considerable number of earlier glasses also present chemical features that suggest the use of plant-based fluxes. As will be discussed below, some variables strongly suggest that these glasses were made with a mixture of plant ash- and mineral-based fluxes, for which reason we have decided to refer to them broadly as IPAN (Intermediate Plant Ash and Natron). It is not immediately clear whether they form a single or separate production traditions and the possible differences or technological links between earlier and later glasses will therefore be examined in terms of possible innovation and exnovation. The main chemical data is compiled in Additional Material-Appendix 1. Although we have tried to be exhaustive in our literature review, it is almost certain that more examples have been published but have escaped our attention.

2. What is plant-ash glass?¹

In the Introduction, we have avoided the use of the expression “plant-ash glass” as much as possible, even though it is regularly used in the literature. It is hoped that the reason for this will become clear below, and perhaps it is better to start by defining what has been referred to as “plant-ash glass” to date. The >1.5 wt % MgO and >1.5 wt % K₂O cut-off point suggested by Lilyquist and Brill (1993) is often used to identify glasses made using plant-based fluxes (e.g. Freestone et al., 2008a; Drauschke and Greiff, 2010; Velde and Motteau, 2013; Jackson and Cottam, 2015; Schibille et al., 2016; de Juan et al., 2019), reflecting the lower presence of these oxides in mineral-based fluxes, while Rosenow and Rehren (2014, 2018) and Oikonomou et al. (2021) also define them on the basis of their elevated phosphate contents.

To the best of our knowledge, significant assemblages of glass that meets these criteria include a characteristic 1st-century CE production of emerald-green glass (Jackson and Cottam, 2015); a number of samples from Bubastis (Lower Egypt), mostly dating to the 1st–2nd century (Rosenow and Rehren, 2014); a group of samples from Armant (Upper Egypt) ranging in date from the 1st century BCE to potentially the 7th century CE (Rosenow and Rehren, 2018); glass from several archaeological contexts roughly dated from the mid-to-late-6th century to the early-to-mid-7th century, like several Visigothic sites in the modern province of Madrid (Spain) (de Juan et al., 2019); Caričin Grad/Iustiniana Prima (Serbia) (Drauschke and Greiff, 2010); Argiroupolis (Crete) (Oikonomou et al., 2021); the dump of a 6th–7th-century secondary glass workshop in Kouklia (Cyprus) (Cosyns et al., 2021); and, now, also Byzantine Malaga (these are samples MAL75–78 in Appendix 1, and are reported here for the first time); and glass from several museum collections,

also roughly dated to the late 6th and early 7th century, including Anglo-Saxon vessel glass found in graves across Kent, in the British Museum (Freestone et al., 2008a), and Byzantine glass weights in the British Museum and the Bibliothèque Nationale de France (Schibille et al., 2016). For the find spots of all potential IPAN glass see Fig. 1, and for a distribution of samples across different sites and chronologies see Table 1.

The new four samples from Malaga were found in a closed context in an area of the city's harbour occupied by port facilities. Specifically, they were found in an early 7th century context interpreted as the collapsed remains of a warehouse with abundant traces of fire, probably related to the fall of the Byzantine city to the Visigoths in the late 610s (Arancibia, 2014). They correspond to four chunks of dark green raw glass (see Fig. 2), found in the company of other archaeological materials, including pottery and a number of fragments of vessel glass (which were found to correspond to natron glass). They were analysed by EMPA for major and minor elements and LA-ICP-MS for trace elements, following the analytical protocols described in Govantes-Edwards et al., (2024). For the precision and accuracy of these analyses see Appendix 2 in Additional Material.

It is important to note that this article deals exclusively with vessel glass, working waste, and raw glass, excluding various forms of strongly-coloured and black-looking glass objects such as beads, tesserae, and bangles. As will be pointed out briefly below, many of these objects published in the literature share important compositional features with our IPAN glasses, but they also present a number of idiosyncratic features that would have made their inclusion in the analysis an excessively complex task for a single paper, although we agree that examining their potential relation with IPAN glass in the future is of the highest interest.

We begin with a very specific type of emerald-green glass characterised by Jackson and Cottam (2015; see also Henderson, 1996), which appears briefly in the first half of the 1st century to decline sharply and disappear mere decades later. This emerald-green glass is compositionally very close to a rarer group of naturally-coloured glasses from the same period (from Adria: Gallo et al., 2013; Herculaneum and Sagalassos: Degryse, 2014; Bubastis: Losogne-Papögnä and Muralto: Arletti et al., 2010; Pompeii: Brill, 1999; Aquileia, Boschetti et al., 2016; Armant: Rosenow and Rehren, 2018), except for the colourants added to the emerald green glass, as will be examined in more detail below. Apart from displaying MgO and K₂O close to or above 1.5 wt%, these glasses are characterised by lower silica and lime than typical Roman natron glasses. This is despite plant ash theoretically contributing lime to the batch. This suggests that the emerald-green glasses were made with a lime-poor silica source or/and that plant ashes low in calcium were used (Jackson and Cottam, 2015). On the other hand, phosphorus, magnesia, and potash in these glasses show a strong to moderate positive correlation with each other (see Table 2), which indicates the use of a single ash type, but are negatively correlated with soda (which can vary widely from sample to sample), which indicates an additional source of soda, likely natron, suggesting the mixture of ashes and natron at the primary stage (arguments to dismiss other possible reasons for the elevated magnesia and potash contents in IPAN glass are found in Section 3.1).

The 1st-to-3rd-century CE glasses from Bubastis (Rosenow and Rehren, 2014) and Armant (Rosenow and Rehren, 2018) and other early naturally-coloured IPAN glasses are, as noted, very similar to this emerald-green glass in their basic composition, with relatively low silica and lime and correlated magnesia, potash, and phosphorus. Sample A-11 from Armant presents exceptionally high magnesia (3.35 wt% MgO), potash (2.81 wt% K₂O), and phosphorus (1.65 wt% P₂O₅), although it is still a good fit for the correlation lines of the other glasses. For a comparison of lime to silica ratios in early IPAN glasses (emerald green and naturally-coloured) and a selection of assemblages of typical early imperial glasses see Fig. 3. Notably, a significant proportion of these glasses correspond to unguentaria. Rosenow and Rehren (2014) compare their glasses with the unusual glasses from the Wadi Natrun reported by Picon et al. (2008) as plant-ash glass, and note significant differences, notably the very high lime (10–16 wt% CaO) and alumina (4–7 wt% Al₂O₃) and very low soda (9.5–12.5 wt% Na₂O) in the Wadi

¹ The analysis presented in this section is based on sizeable and archaeologically consistent assemblages or in assemblages chosen because they include glass that is deemed to be particularly significant (for instance, ‘raw’ glass). Other isolated examples of what we believe to be IPAN glass exist, and can be found in Appendix 1 with the appropriate references



Fig. 1. Find spots and size of assemblages of IPAN glass dated to the 1st-2nd century CE (a); 3rd-5th century CE (b); and 6th-7th century CE (c). The Byzantine glass 'assemblage' is not situated in a specific find spot because it is made up of unprovenanced museum holdings.

Natron glasses. The relationship between different flux-discriminating oxides in IPAN glasses is also illustrated by Fig. 4.

The main difference, therefore, between the emerald-green glasses (n: 59) and other, naturally-coloured early Roman IPAN glass in our database (n: 13) lies in the additives that give the former their characteristic colour. The emerald-green glasses present high quantities of copper (ranging from 1.23 wt% to 3.16 wt% CuO) and elevated tin (up to 0.26 wt% SnO₂), and sometimes lead (up to over 0.5 wt% PbO), perhaps as a result of the use of scrap bronze as colouring additive (Henderson, 1996: 190). This is in contrast with the naturally-coloured glasses, in which these elements are present only in small quantities (av. 35 ppm Cu, 5 ppm Sn, and 31 ppm Pb).²

² Although A-6 from Armant displays 221 ppm Cu, 31 ppm Sn, and 180 ppm Pb, this is perhaps more suggestive of some degree of recycling than deliberate addition. One of the variables used to detect recycling practices in natron glasses is the presence above geological thresholds of colourants and opacifiers in naturally-coloured glasses (Jackson, 1996; Paynter and Jackson, 2016; Freestone, 2015). The thresholds used here are based on data from glass believed not to have been recycled: 50–100 ppm Cu; 50–75 ppm Pb; 25 ppm Sn; 10–20 ppm Sb (after Rehren and Brüggler, 2015; Rosenow and Rehren, 2018). The reported strong green colour in the Armant glasses is therefore most likely due to their thickness and the natural iron oxide content present.

This remarkable similarity is illustrated by Table 3. It seems therefore safe to assume that in the emerald-green glasses the colourants, mostly copper, were added to a base glass represented by the naturally-coloured samples. As such, unless otherwise stated, for the emerald-green glasses, hereafter we shall be using normalised amounts, resulting from subtracting copper contents and normalising all other elements to the total of the sum of all elements.

Skipping momentarily ahead, the following major assemblages of archaeological glass with magnesia and potash contents close to or above 1.5 % are dated to a relatively narrow timespan from the mid-to-late 6th to the early-to-mid-7th century. The two largest assemblages were labelled MAGBY (Magnesium Byzantine Glass) by Schibille et al. (2016) and de Juan et al. (2019), on account of their high magnesia content. Both these studies point out the positive correlation of magnesia, potash, and phosphorus (see Table 2), and to some affinity between MAGBY and Foy 2.1 glasses, for instance in terms of titanium, zirconium, and iron, although alumina, another silica-related oxide, is somewhat lower in MAGBY than in Foy 2.1 glasses (Schibille et al., 2016; de Juan et al., 2019) (see Table 4 for a comparison of the average contents found in the main assemblages).

The other 6th-7th century assemblages are in nearly all respects identical to the MAGBY assemblages, with minimal variations, such as slightly elevated soda in Crete and Britain, high relative alumina in Armant, and elevated silica again in Crete and in some Byzantine glass weights.



Fig. 1. (continued).

How do these late glasses compare with early IPAN glasses? The late glasses present slightly higher silica and strontium (av. 692 vs 456 ppm Sr) and significantly more lime than the earlier glasses – although the lime/strontium ratios are similar, which would be consistent with, but does not prove, the same or similar lime source (but see below) – as well as lower alumina, phosphorus, and barium (av. 266 vs 311 ppm Ba). For a comparison of the CaO/Sr and SiO₂/Al₂O₃ ratios of IPAN glasses and typical natron glass groups, for comparative purposes, see Fig. 5.

Concerning mid-IPAN glasses analysed by Rosenow and Rehren (2014, 2018) and Brill (1999), mostly dated to the 4th–5th centuries (therefore, chronologically in between early and late IPAN glasses), the greatest issue is that they were dated solely based on typology, so their chronology is imprecise, and their relatively small number. At any rate, although these limitations must be kept in mind at all times, they are compositionally similar to both early and late IPAN glasses, although more to the latter, especially on account of their high lime content, suggesting similar ingredients and production processes.

Finally, several authors have divided glasses with plant ash into low- and high-Mn types. Plotting MnO against the sum of main plant-ash discriminant oxides (potash, magnesia, and phosphorus pentoxide) shows two distinct clusters of low-Mn (0.00–0.35 wt% MnO) and high-Mn samples (1.75–2.55 wt% MnO) (Fig. 6, which includes some typical natron glass types for comparative purposes), with a large number of glasses forming a much less defined point cloud in between, including most early IPAN glasses. Freestone et al. (2008a) explained high-Mn compositions as the result of the addition of Mn-rich potassic ash,

such as beech-wood ash, which was commonly used in medieval northern European glassmaking (Wedepohl, 2003), to natron glass. After their analysis of an assemblage of 6th-century glass in the Lower Danube, Cholakova et al. (2016) pointed out the strong correlation between manganese and strontium in Foy et al.'s (2003) 2.1 glass, and a moderately strong correlation is found in the high-Mn late IPAN (R: 0.58) and the early IPAN glasses, (R: 0.61) which appear to form a continuum with the Foy 2.1 glasses in this variable (which is perhaps indication that late IPAN and Foy 2.1 glasses are in some way related, of which more below), while low-Mn late and mid IPAN glasses also form a moderate correlation line of their own with Sr (R: 0.56) (Fig. 7). De Juan et al. (2019) argue that high-Mn samples present higher magnesia, alumina, and iron than low-Mn samples. The data probably suggests that Mn was added to some late IPAN glasses, presumably with decolouring purposes.

3. Discussion

So far, we have identified two chronologically, compositionally and, for the most part, visually distinct groups of vessel IPAN glass (as noted, most early IPAN is emerald green and typologically narrow, whereas mid and late IPAN glasses are all naturally-coloured and typologically indistinguishable from other late Roman and late Antique glasses), including just under 20 % of glasses to which manganese was added, presumably with (de-)colouring purposes. The variability in composition and dating, however, does not necessarily imply two distinct and



Fig. 1. (continued).

focussed production events or traditions. As noted, in most variables, the glasses that we have labelled as IPAN present a fairly regular compositional profile, and even in those variables in which the differences between early, mid, and late examples are greatest, there are significant overlaps. It will thus be argued that, rather than different groups, these IPAN glasses represent a single, long-running tradition with gradual changes over time, not unlike Levantine glasses over the same period.

3.1. Compositional features

Probably one of the most outstanding features of IPAN glasses is their low content of MgO and K₂O (just under 2 wt% MgO and just over 1.5 wt% K₂O on average) compared with earlier, coeval, and later glasses known to have used plant ash as flux. For instance, the Parthian and Sasanian glass examined by Mirti et al. (2008) presents an average of 5.24 wt% MgO and 3.37 wt% K₂O; and the early Islamic glass reported by Phelps (2018) has on average 2.89 wt% MgO and 2.44 wt% K₂O. The only element that breaks this pattern is the higher content of phosphorus pentoxide found, especially but not only, in early IPAN glasses (av. 0.65 wt% P₂O₅). Different explanations have been offered for these relatively low concentrations of magnesium and potash.

- a) That the glasses that we have been examining were fluxed with plant ash *in addition* to natron (Drauschke and Greiff, 2010);
- b) that potassic ashes were being added to existing natron glass to prolong its use-life in conditions of limited fresh glass supply

(Freestone et al., 2008a), or that phosphorus-rich ashes were added to existing natron glass (Jackson and Cottam, 2015);

- c) that the elevated magnesia and potash levels compared to natron glasses could be the result of contamination from firewood combustion gases within the furnace (Rehren and Freestone, 2015; Rosenow and Rehren, 2014), an effect reported by Sarah Paynter (2008) following experimental work undertaken by Taylor and Hill (2008), as recently demonstrated in experimental work by Lucas (2022); and,
- d) another possibility is that plant-ash glass (the only plausible candidate is probably Sasanian glass) was mixed with natron glass.

Possibilities b), c), and to an extent d) seem to be ruled out by the apparent stability in terms of silica-discriminant oxides and elements. If potash, magnesia, and phosphorus were being added to glass, deliberately in the form of ash or accidentally with combustion gases, this effect is to be expected to be found in glasses from different production regions, but the elements brought together with the silica seem to point to a similar origin for all IPAN glasses. In addition, if Sasanian glass was being mixed with natron glass, the contents in silica-discriminant oxides of the resulting glass would be expected to fall in an intermediate position between the two types, but, as illustrated by Fig. 8, this is not the case.

Considerable differences exist between IPAN glass and LBA plant-ash glasses (for LBA plant-ash glasses see Shortland et al., 2018). Differences in the absolute amounts of magnesia and potash are easily explained by

Table 1
Number of IPAN glass samples examined in this article per site and chronological distribution.

	Total IPAN glasses (n = 180)		
	Early IPAN (n = 72)	Middle IPAN (n = 17)	Late IPAN (n = 91)
Adria	5		
Herculaneum	2		
Barzan	11		
Colchester	16		
Fréjus	2		
Trojane	2		
Ribnica	19		
Bubastis	3		
Aosta	1		
Losogne- Papôgna	1		
Muralto	1		
Pompeii	1		
Sagalassos	1		
Aquileia	1		
Armant	2	11	
Bubastis	1		
Augusta Emerita	1		
Iulia Traducta	2		
Karanis		1	
Sedeinga		4	
San Martino di Ovaro		1	
Diana			2
Madrid (various sites)			25
Caricin Grad			2
Rethymnon			14
Malaga			4
Britain (various sites)			10
Podvršje			2
Byzantium (unclear sites)			18
Vicq			2
Polis – Cyprus			1
Cickini			2
Kouklia			3
San Genesio			3
Grado			2
Venice			1

For bibliographic references and typological and colour description, see Additional Material.

the mixture of plant ashes and natron in IPAN glass. Potash to phosphorus ratio and absolute phosphorus content likely suggest the use of different plant species as ash sources in LBA- and Roman-period glassmaking. Perhaps the answer lies with *Suaeda aegyptiaca*, a halophytic

species abundant in Egypt whose phosphorus contents has been shown, in at least one sample (WM2 in Tite et al., 2006), to significantly surpass that of other plant species typically regarded as likely sources of ash in glassmaking. In addition, both the ash from this species and IPAN glasses present a comparatively high soda to potash and low normalised lime-plus-magnesia ratios (see Table 5). The differences with Sasanian glass are also obvious, again suggesting the use of different plant species. see Fig. 9 for comparison of IPAN glasses and LBA and Sasanian glass.

It is worth mentioning that the chemistry of ashes allegedly used in glassmaking is still poorly understood, because comparatively few analyses have been published to date. Also, this is a very complex issue, because the composition of plant ashes is notoriously variable, as it is affected by a large number of factors (e.g. rainfall patterns/seasonal variations, underlying geology) (Tite et al., 2006; Barkoudah and Henderson, 2006). However, based on the relatively low potash content, it is possible that other soda-rich plant species with relatively low potash levels were (also?) used, such as *Salsola soda*, *Anabasis syriaca*, and *Salsola Jordanicola*. This remains, in any case, an extremely complex issue, and a much greater understanding of the chemistry of the plants used in glassmaking (and, potentially, experimental work with different plant species), is probably necessary to find further clarity. This is

Table 2
Correlations between the average contents of phosphorus pentoxide, magnesia, potash, and soda in emerald-green, naturally-coloured early IPAN, mid-IPAN, and MAGBY glasses.

Emerald green glass ^a	K ₂ O	MgO	Na ₂ O
P ₂ O ₅	0.88	0.84	−0.67
K ₂ O	–	0.66	−0.72
MgO	–	–	−0.44
Nat-col early IPAN	K ₂ O	MgO	Na ₂ O
P ₂ O ₅	0.88	0.57	−0.39
K ₂ O	–	0.40	−0.64
MgO	–	–	−0.08
Mid-IPAN	K ₂ O	MgO	Na ₂ O
P ₂ O ₅	0.77	0.72	−0.27
K ₂ O	–	0.80	−0.57
MgO	–	–	−0.33
MAGBY	K ₂ O	MgO	Na ₂ O
P ₂ O ₅	0.72	0.69	−0.59
K ₂ O	–	0.54	−0.61
MgO	–	–	−0.46

^a Jackson and Cottam (2015).



Fig. 2. Three of the four chunks of raw glass found in an early 7th-century context in Byzantine Malaga.

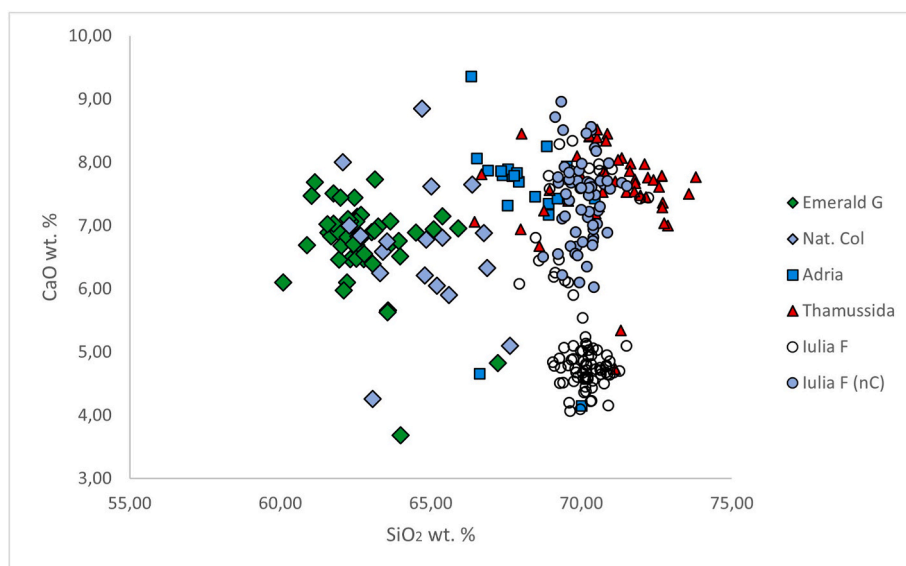


Fig. 3. Comparison of silica and lime contents of 1st century emerald-green and naturally coloured IPAN glass and 1st to 3rd century naturally-coloured and Sb-decoloured natron glass, including samples from Adria (Gallo et al., 2013), Thamussida (Gliozzo et al., 2013) and the *Iulia Felix* shipwreck (Silvestri et al., 2008; Silvestri, 2008). Overall, emerald green IPAN glasses present slightly lower silica and lime than their naturally-coloured counterparts, but this is likely the result of the addition of colourants to a base glass (see below), leading to the dilution of the remaining elements. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

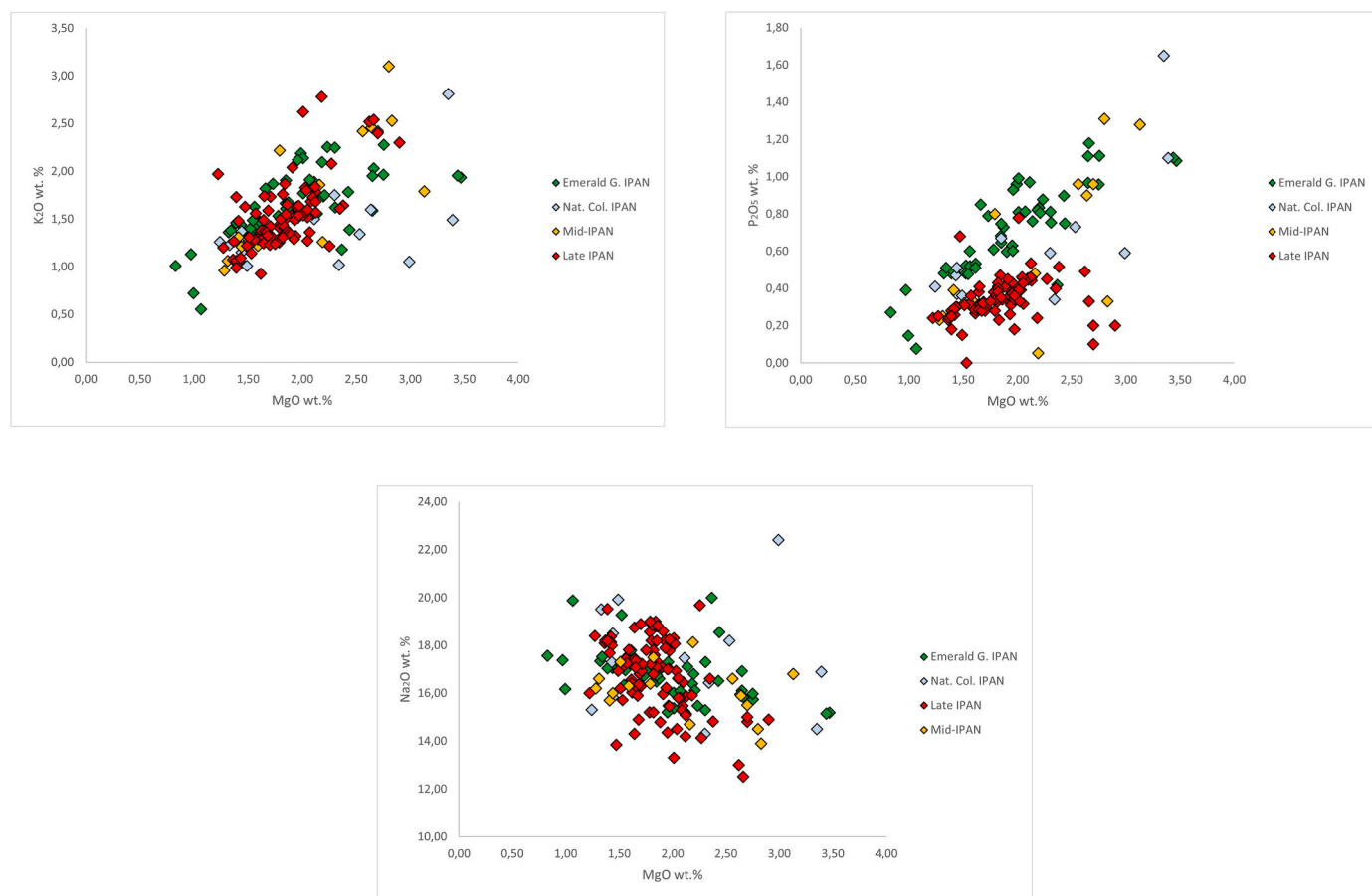


Fig. 4. Comparison of magnesia and potash (4a), magnesia and phosphorus (4b), and magnesia and soda (4c) contents in IPAN glasses. The strong to moderate correlation between magnesia, potash and phosphorus suggests that these elements came into the batch mostly with one ingredient, likely plant ash (as they are present in natron in only small quantities), while the negative correlation with soda indicates that Na₂O was probably introduced into the glass with more than one Na-rich ingredient.

Table 3

Average compositions of major and minor elements of early green emerald and naturally-coloured IPAN glasses after the removal of copper and the normalisation of remaining elements in the former.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	Cl	K ₂ O	CaO	MnO	Fe ₂ O ₃	TiO ₂
Emerald n = 49	17.13	1.98	2.42	64.22	0.72	0.27	0.95	1.68	6.87	0.81	1.23	0.19
	s.d: 1.10	s.d: 0.56	s.d: 0.39	s.d: 1.27	s.d: 0.25	s.d: 0.05	s.d: 0.10	s.d: 0.37	s.d: 0.68	s.d: 0.25	s.d: 0.16	s.d: 0.06
Naturally-coloured n = 9	17.22	2.22	2.11	64.75	0.52	0.15	0.52	1.46	6.66	0.94	1.29	0.16
	s.d: 1.80	s.d: 0.78	s.d: 0.22	s.d: 1.58	s.d: 0.52	s.d: 1.12	s.d: 0.44	s.d: 0.52	s.d: 0.97	s.d: 0.62	s.d: 0.33	s.d: 0.06

Table 4

Average major elements and zirconium contents of various assemblages of IPAN glasses (green) and late Roman and late antique natron glasses (blue).

Assemblages	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	Fe ₂ O ₃	TiO ₂	Sb ₂ O ₅	Zr
Early IPAN n=59	16.80 s.d:1.22	1.99 s.d: 0.60	2.33 s.d: 0.39	62.91 s.d: 1.45	0.72 s.d: 0.30	1.64 s.d: 0.39	6.68 s.d: 0.72	1.19 s.d: 0.19	0.18 s.d: 0.06	0.24 s.d:0.15	88 s.d:32
Mid IPAN n=17	16.10 s.d:1.08	2.04 s.d:0.62	2.35 s.d:0.71	64.58 s.d:3.69	0.54 s.d:0.40	1.74 s.d:0.65	8.47 s.d:1.21	1.50 s.d:0.67	0.16 s.d:0.07	0.05 s.d:0.02	101 s.d:26
LATE IPAN	Madrid (MAGBY) n=25	1.90 s.d:0.20	2.00 s.d:0.35	64.80 s.d:1.53	0.40 s.d:0.06	1.50 s.d:0.18	9.3 s.d:0.69	1.4 s.d:0.50	0.20 s.d:0.03	0.00	84 s.d:20
	Crete n=14	1.60 s.d:0.80	1.90 s.d:0.20	67.30 s.d:0.58	0.30 s.d:0.09	1.30 s.d:0.17	8.10 s.d:0.56	1.0 s.d:0.11	0.20 s.d:0.03	0.01 s.d:-	85 s.d:17
	Britain n=10	1.87 s.d:1.50	2.12 s.d:0.26	64.13 s.d:1.76	0.29 s.d:0.09	1.51 s.d:0.27	8.90 s.d:1.07	1.11 s.d:0.30	0.17 s.d:0.04	-	-
	Byzantium? (MAGBY) n=18	1.82 s.d:1.67	2.02 s.d:0.26	66.61 s.d:1.55	0.38 s.d:0.12	1.60 s.d:0.43	8.68 s.d:0.80	1.13 s.d:0.38	0.17 s.d:0.02	0.01 s.d:-	90 s.d:19
	Raw glass n=6	1.81 s.d:0.28	1.60 s.d:0.19	64.38 s.d:1.02	0.37 s.d:0.07	1.50 s.d:0.35	8.47 s.d:0.58	0.82 s.d:0.06	0.15 s.d:0.00	-	78 s.d:4
NATRON	Foy 2.1	1.13	2.47	66.34	0.15	0.77	8.58	0.94	0.14	0.02	75
	Foy 2.1 (h-Fe)	1.30	2.80	64.60	0.20	0.90	7.70	2.30	0.20	0.01	93
	Lev 1	0.70	3.10	69.30	0.10	0.60	9.20	0.50	0.10	0.00	41

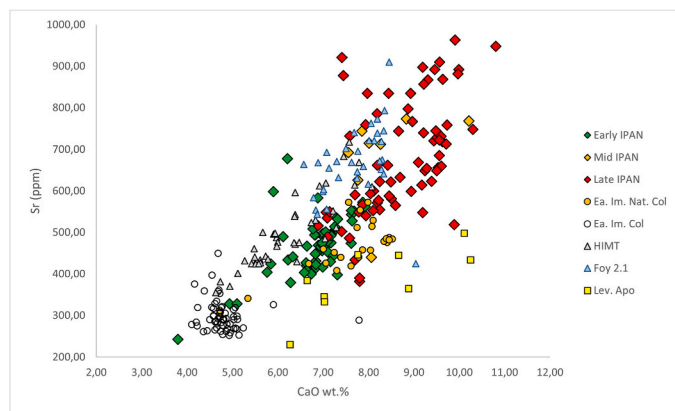
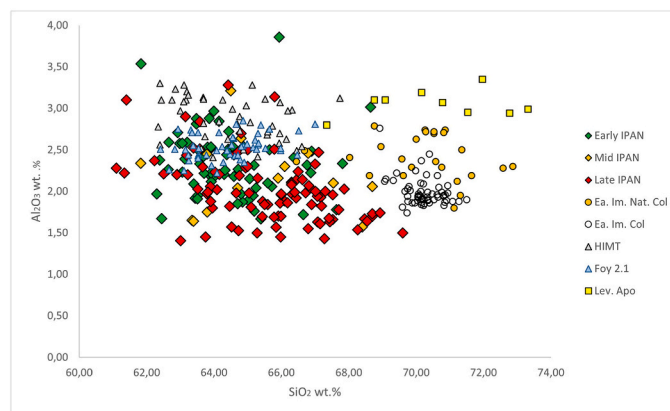


Fig. 5. Comparison of lime and strontium (5a) and silica and alumina (5b) contents of IPAN glasses and some groups of natron glass – early imperial naturally coloured (Gallo et al., 2013), early imperial colourless (Silvestri et al., 2008), HIMT (Foy et al., 2003), Foy 2.1 (Foy et al., 2003) and Levantine I from Apollonia (Freestone et al., 2008b). These comparisons reflect that early, middle, and late IPAN glasses present significant overlaps even in those compositional variables in which they differ the most.

complicated even more by the possibility that the amount of ash introduced in glass batches varied depending on the availability of natron (see below); in other words, the differences in magnesia, potash, and phosphorus could be the result not only of the use of various species grown and harvested in differing conditions, but also of the relative quantity of ash and natron introduced in each batch.

At the same time, a degree of overlapping with some natron glasses in terms of flux-discriminant oxides has been noted, notably with the Foy 2.1 type (Foy et al., 2003), which tends to display elevated magnesia and potash relative to other natron glasses. This raises the question of whether the 1.5 wt% threshold of magnesia and potash typically used to distinguish mineral from plant-based fluxes can be upheld. Rosenow and Rehren (2018) suggested using the sum of plant-ash discriminative

oxides as an alternative distinguishing variable, but this also leads to a slight overlap. This is perhaps indicating that our late IPAN and Foy 2.1 glass are related, and this may be supported by additional evidence, such as high concentrations of some elements generally brought into the glass with the silica source, such as titanium and zirconium (see Table 4), which suggest a common origin in Egypt (Rosenow and Rehren, 2014; Schibille et al., 2016); a conclusion reinforced by the chromium and lanthanum contents (Jackson and Cottam, 2015). This similarity is also found in the strontium-bearing components of the batch. In many natron glasses, this is held to be primarily shell, which is typically made of the CaCO₃ polymorph aragonite, whose capacity to incorporate strontium far surpasses that of the constituent of limestone calcite (Freestone et al., 2000, 2003). This is taken by Schibille et al. (2019) to indicate the use of

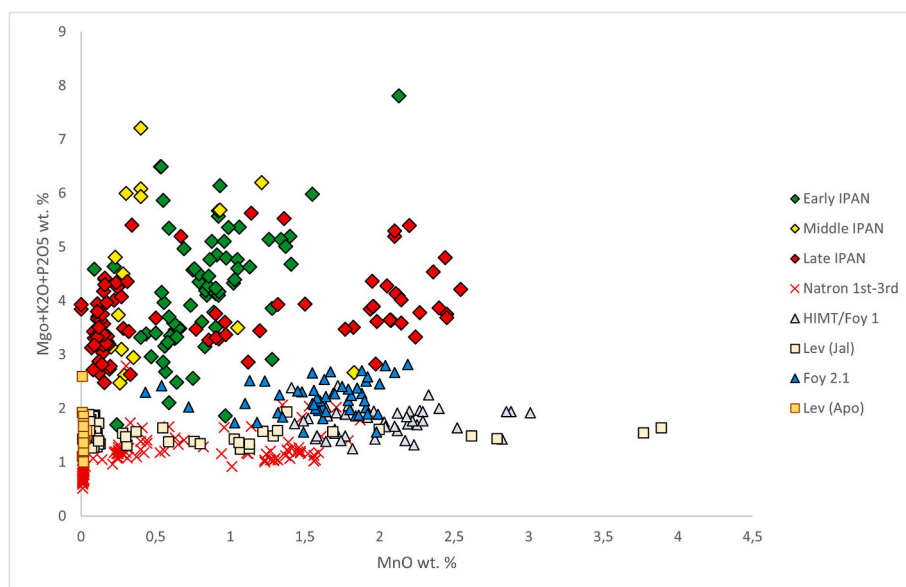


Fig. 6. Comparison of MnO and MgO + K₂O + P₂O₅ contents in IPAN glass and several Roman, late Roman, and late antique glass groups. The plot shows two distinct clusters of high- and low-Mn samples, and a scatter of samples in between (made up largely of early IPAN glass). Data for 1st-3rd century natron glasses: [Gliozzo et al., \(2013\)](#); [Silvestri et al., \(2008\)](#); [Brill \(1999\)](#); Foy 1/HIMT: [Foy et al., \(2003\)](#); Lev (Jalame): [Brill \(1999\)](#); Foy 2.1: [Foy et al., \(2003\)](#); Lev (Apollonia): [Freestone et al., \(2008b\)](#).

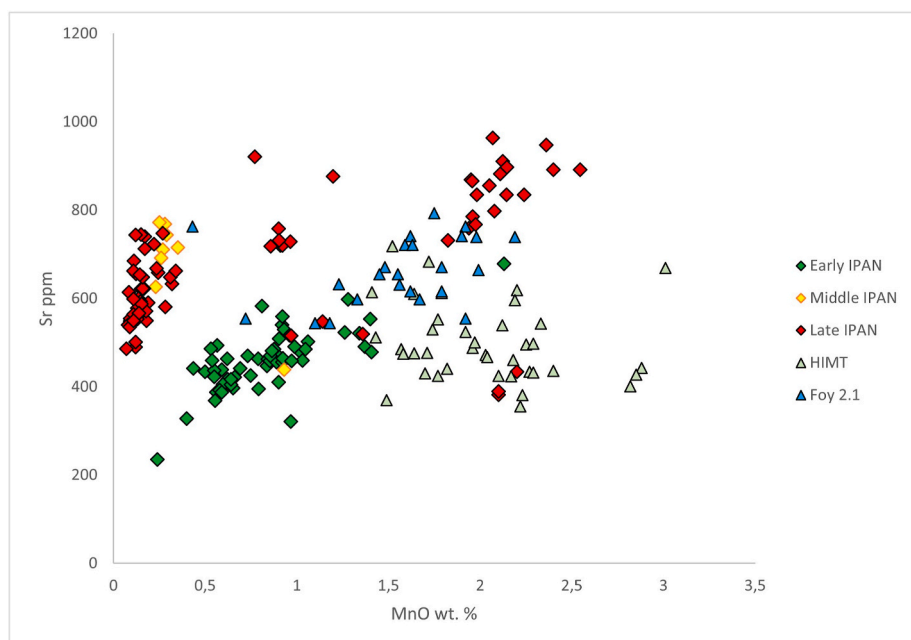


Fig. 7. Comparison of MnO and strontium contents in IPAN and Foy 2.1 glasses. Data for HIMT and Foy 2.1 glass was taken from [Foy et al., \(2003\)](#). The data presents two clear correlation lines, one of low-Mn samples and another with a wider range of manganese contents, in which the lower-Mn samples (mostly early IPAN) appear to be linked with high-Mn ones (made up of late IPAN glasses) by Foy 2.1 samples.

shell-rich coastal sands. The Sr and CaO of IPAN and Foy 2.1 glasses result in a similar Sr/CaO ratio to aragonite (IPAN glass: 0.017-0.006; Foy 2.1: 0.015-0.006; aragonite: 0.016-0.003). If the glassmaking sands of both categories were similar then a combination with lime-bearing ash in the case of IPAN glasses might be expected to have resulted in a different ratio, and this would suggest the use of a low-lime sand in their production. However, this is not conclusive, as it must be acknowledged that some plant ashes have Sr/CaO ratio which are themselves similar to aragonite (e.g. *C. murale* – 0.010 – and the genus

Suaeda – 0.010–0.013 – based on data from [Barkoudah and Henderson, 2006](#)). At any rate, the lower alumina found in the late IPAN glasses compared to Foy 2.1 seems to rule out the use of the same sand sources. Future data on strontium isotopes could be of help to solve these doubts, as the ratios of shell- and plant ash-borne strontium could differ (but not necessarily).

To conclude our reflections about possible identification criteria for IPAN glass, although a strict cut-off line at 1.5 wt% of magnesia and potash has been shown not to be completely reliable, it remains a useful

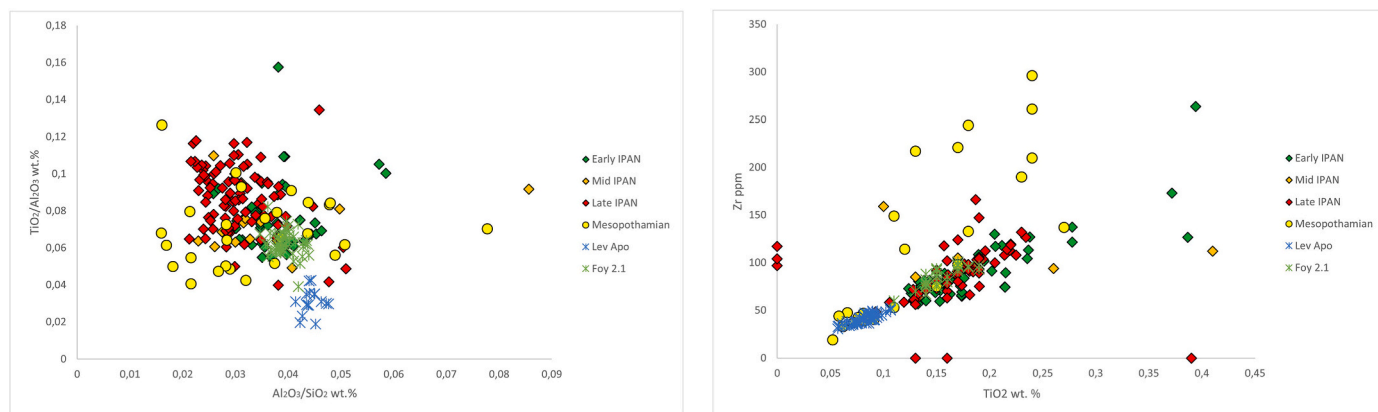


Fig. 8. Comparison of alumina to silica ratio and titanium to silica ratio (8a) and titanium and zirconium contents (8b) in IPAN glasses, Mesopotamian glass (Mirti et al., 2008), Foy 2.1 glass (Foy et al., 2003), and Levantine-Apollonia glass (Freestone et al., 2008a). If the magnesia and potash content of IPAN glass was the result of mixing plant ash-glass (the only candidate would be Sasanian glass) and natron glass, IPAN glass should appear in an intermediate position between Sasanian and natron glasses in terms of silica-related oxides and elements, such as silica, alumina, titania, and zirconium. These figures illustrate that this is not the case, rather suggesting some affinity between IPAN and Egyptian glasses in terms of silica sources.

Table 5

Composition of IPAN, plant ash-glasses, and several plant species potentially used as a source of flux in terms of contents in flux-discriminant oxides, soda to potash ratio, and normalised lime plus magnesia content. The compositions of the plant species listed in the second block of the table (*) can be found in Tite et al. (2006), those in the third block (**) in Ashtor and Cevdalli (1983), and those in the fourth block (***) in Barkoudah and Henderson (2006).

Glass group	Na ₂ O	K ₂ O	CaO	MgO	P ₂ O ₅	Na ₂ O/K ₂ O	CaO + MgO/Na ₂ O + K ₂ O
						Soda to potash ratio	Normalised lime plus magnesia ratio
Early IPAN	16.80	1.64	6.68	1.99	0.72	10.24	0.47
Middle IPAN	16.10	1.74	8.47	2.04	0.54	9.25	0.58
Late IPAN	16.72	1.53	8.69	1.84	0.34	10.92	0.57
Sasanian n = 28	15.84	3.37	6.15	5.24		4.70	0.59
	s.d: 1.61	s.d: 0.61	s.d: 1.10	s.d: 1.63			
Egyptian LBA n = 170	18.07	1.97	7.58	4.25	0.16	9.17	0.59
	s.d: 1.99	s.d: 0.71	s.d: 1.60	s.d: 0.78	s.d: 0.06		
Mesopotamian LBA n = 28	16.49	2.83	6.61	4.41	0.21	5.82	0.57
	s.d: 1.84	s.d: 0.66	s.d: 1.52	s.d: 1.21	s.d: 0.07		
Plant Species *							
<i>Soda di Catania</i> (Sicily)	23.0	5.7	9.0	2.5	0.6	4.0	0.40
<i>Salsola kali</i> (Sicily)	17.0	9.0	16.0	11.0	2.4	1.9	1.04
<i>Salicornia</i> (Venice)	35.0	4.0	5.0	5.4	0.6	8.8	0.27
Fern (Venice)	0.4	25.5	18.0	8.0	4.0	0.02	1.00
<i>Suaeda aegyptiaca</i>	43.4	6.5	5.2	3.9	5.3	6.67	0.18
Plant species **							
<i>Salsola kali</i>	14.3	15.5	14.4	9.0		0.9	0.80
<i>Salsola soda</i>	44.0	6.0	3.3	1.6		7.3	0.09
<i>Salsola soda</i>	42.0	7.5	3.8	2.0		5.6	0.11
Fern	0.41	25.5	17.9	8.1		0.01	1.00
<i>Soda di Catania</i>	23.0	9.6	9.3	2		2.39	0.34
Plant species***							
<i>Anabasis syriaca</i>	31.60	6.60	5.28	5.12	0.57	4.78	0.27
<i>Salsola jordanicola</i>	28.60	10.70	1.96	2.44	1.00	2.67	0.11

See Table 4 for number of samples and standard deviation of IPAN glasses.

shorthand tool to be used in combination with other variables (perhaps a flexible 3–3.5 wt% MgO + K₂O + P₂O₅). It must, at the same time, be recognised that the boundaries between MgO- and K₂O-rich natron glass and IPAN glass must remain somewhat fuzzy (note the three spikes formed by various groups of natron glass in Fig. 10), especially because any overlap of the primary groups is bound to be compounded by the inevitability of recycling. Therefore, it is suggested that the traditional thresholds should be regarded as merely indicative, rather than decisive.

At any rate, the fact that the magnesia and potash levels are sometimes close to those displayed by pure natron glass probably indicates that the amount of ash in the batch was not particularly large in comparative terms. At the same time, taken as a group, the range of flux-discriminant oxides in IPAN glasses is fairly wide (the sum of potash, magnesia, and phosphorus can be as low as 1.69 wt% and as high as

7.81 wt%), which, as previously noted, can reflect both the use of plant ashes with different characteristics and the natron/plant ash ratio used in specific batches.

3.2. Early IPAN glass: multiple traditions?

As discussed above, there are enough chemical similarities between early, middle, and late IPAN glasses to argue for some affinity between them, while recognising that they are not entirely the same. In addition to these chemical differences, early IPAN glasses clearly stand out compared to middle and late IPAN glass, in terms of colour (with emerald green glasses) but also of a preference for certain shapes (e.g. so-called ceramic forms and *unguentaria*) and the avoidance of others. As noted, some examples of copper-red, cobalt blue, or black-appearing

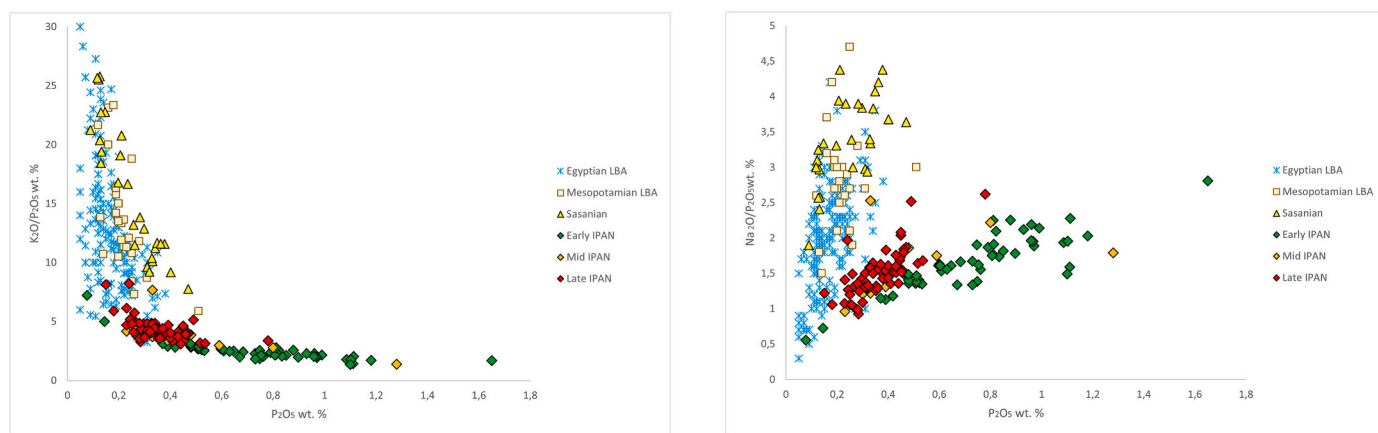


Fig. 9. Comparison of phosphorus and potash to phosphorus ratio (9a) and phosphorus and soda to phosphorus ratio (9b) of IPAN glass and glasses known to have used plant ash as flux (data for LBA glasses from Shortland et al., 2018; and for Sasanian glass from Mirti et al., 2008). These clearly show that IPAN glass, particularly early samples, presents significantly higher phosphorus, while the trend lines likely indicate the use of different plant species.

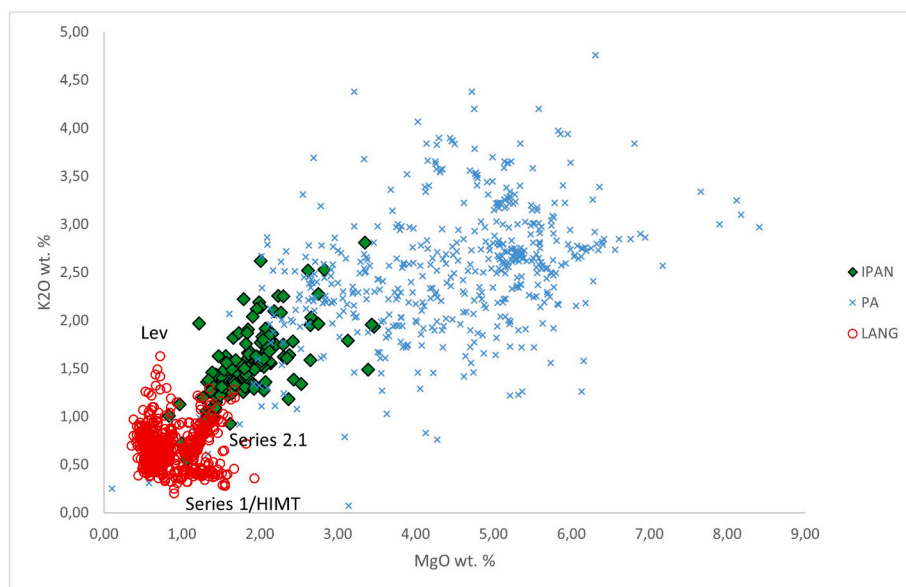


Fig. 10. Comparison of magnesia and potash contents, which are often used to distinguish between natron (Late Antique Natron Glass: LANG, including Levantine, Foy 2.1 and Foy 1/HIMT glasses) and plant-ash glass (PA). Data for Levantine glasses from: de Juan et al. (2019); Ali and Abd-Allah (2015); Ceglie et al. (2015); Wolf et al. (2005); Freestone et al. (2008b); Freestone et al. (2000); Brill (1999); data for Foy 1/HIMT glass from Rosenow and Rehren (2018); Siu et al. (2017); Schibille et al. (2016); Neri and Verita (2013); Palomar et al. (2012); Foy et al. (2003); data for Foy 2.1 from de Juan et al. (2019); Foy et al. (2003); plant-ash glass data from Lilyquist and Brill (1993); Mirti et al. (2008); Carmona et al. (2009); Duckworth et al. (2015); de and Schibille, 2017; Phelps (2018); Schibille et al. (2018); Shortland et al. (2018); Govantes-Edwards et al. (2024).

opaque glass, in the form of tesserae, bangles, or mosaic vessels, among other shapes. (e.g. Moretti and Gratuze, 2000; Nenna and Gratuze, 2009; Van der Linden et al., 2009; Cosyns, 2011; Paynter and Kearns, 2011) present compositional similarities with the early IPAN glasses, aside from the colourants used.

All of this makes it plausible to argue for a relatively concentrated glass industry that specialised in strongly-coloured glasses, as put recently by Rehren and Cholakova (2024) for HIT glass and its strong link to cobalt blue coloration. For emerald and naturally-coloured early IPAN glass there were potentially several production centres, as suggested by the relatively wide range of alkalis found in the glass (Jackson and Cottam, 2015) (although the great variability in composition of plant ash must be kept in mind at all times, see above). Whether these glasses were distributed through different channels from those travelled by natron glass is unclear at this stage. Should these ideas be correct, this

specialised glass production is likely to have been in a much smaller scale than the major natron-based operations.

The picture presented by late antique IPAN glass is completely different. Here, instead of a specialised production and a relatively narrow range of products,³ we have standard everyday shapes (see for instance Foy, 1995) that cannot be visually distinguished from their counterparts made with natron glass. In addition, the size of the assemblages is not negligible, and in some sites these glasses account for a significant proportion of all the glass attested. As such, we need to

³ Concerning early IPAN, we also have to take into account that these glasses are dated to that transitional period shortly after the invention of blowing, so perhaps a more limited selection of vessel shapes is to be expected, regardless of the type of glass used.

examine the possibility that the greater prevalence and reach of this glass was filling a gap in supply.

The key to answer this question may be in the intermediate period (2nd to mid-6th-century), in which the number of known IPAN samples and their geographical distribution shrinks dramatically. [Rosenow and Rehren \(2018\)](#) – like [Jackson and Cottam \(2015\)](#) for earlier emerald green glasses – argue for the possible regional importance, and by extension likely production, of IPAN glass in Upper Egypt. To date, only one sample has been identified outside Upper Egypt and northern Sudan, and it is plausible to argue that the use of plant ashes as flux there could have been driven by relative distance from natron sources, perhaps far enough to cross a tipping point beyond which the use of local plant ashes in smaller production units is more advantageous than the import of either relatively sizeable quantities of mineral natron or fresh natron glass. Let us not forget that different traditions and scales of industries can coexist in complex markets, and this is a plausible scenario for the early period, when large scale operations met most demand with natron glass while a much smaller-scale industry supplied specialised products abroad as well as serving local everyday needs. We have suggested above that the silica source was a lime-poor inland sand; while the Sr-isotope ratios of natron-based Egypt I ([Barfod et al. 2020](#); [es Fig. 3](#)) and Egypt II ([Freestone et al., 2003](#)) glasses are consistent with inland sands, the CaO contents of Egypt I are low, at around 3 %, confirming the use of such sands in glassmaking (also [Rehren and Rosenow, 2020](#)), which could perhaps be located in Egypt. Once the demand for the specialised product declined abroad, this small-scale industry could have continued meeting local needs, until global conditions changed (see below) from the 6th century onwards, creating a new demand, in this instance for everyday glass items.

3.3. The organisation of glassmaking

What are the implications of these ideas concerning the fit of IPAN glass in a natron-dominated industry?

It is by now widely accepted that most of the glass produced during the Roman and Late Antique periods was melted using Egyptian natron as a flux in a limited number of locations, namely the Levantine coast and Egypt ([Nenna, 2015](#); [Freestone et al., 2000](#)).

Although our knowledge about the organisation of primary glassmaking is very limited, the vast tank furnaces used must have involved significant capital investment to procure the facilities, raw materials, fuel, labour, and specialised knowledge. Although it is likely that basic knowledge about the craft of glassmaking was relatively widespread (e.g. Pliny's *Natural History* XXXVI, LXV-LXVI, for instance, mentions the right ingredients) the successful operation of tank furnaces, in which a large number of variables can go wrong, must have required highly-specialised skills and expertise ([Freestone, 2023](#)), especially if a sizeable investment was at stake. In addition, operations on this scale are only undertaken in the right institutional conditions, with regular and predictable outlets for the finished product. How this trade was operationalised, however, is unclear, as our evidence is almost entirely limited to that yielded by shipwrecks, which suggest a wide spectrum of possibilities (see [Govantes-Edwards et al., 2025](#)). For Late Antiquity, it has been suggested that non-strategic goods, such as glass, largely piggy-backed other commodities of greater political and economic importance ([Wickham, 2005](#)) such as those being moved across the Mediterranean by the Byzantine *annona* system ([McCormick, 2001](#)). Some evidence of this for glass is being found, for instance in the Byzantine province of *Spania* (c. 550-c. 621) ([Vizcaino, 2007](#)).

However, the evidence presented above clearly suggests that there were market niches for types of glass other than 'normal' Roman glass, and that these types of glass appears to have been produced in a smaller scale than pure-natron glass. It is at this stage impossible to draw even a rough outline of how this glassmaking industry was organised, whether it was based on centralised or more localised workshops, and how the glass was commercialised. Let us recall that even if we have found some

of the primary furnaces in which natron glass was melted from batch, most of the details of the trade in this glass remain obscure. The contemporary Sasanian glass industry is equally elusive as far as the organisation of production goes. Although we are beginning to have an increasingly reliable picture of the compositional features of Sasanian glass, next to nothing is known about production areas ([Schibille, 2022](#)). In any case, compositional variability, affecting both silica- and flux-related elements (see for instance [Cheng et al., 2024](#)) suggests the operation of multiple small-scale primary workshops, a phenomenon mirrored by early Islamic glass in Central Asia ([Schibille et al. 2022, 2024](#)). It is also worth recalling that, while in the Roman Empire craftspeople were organised in professional corporations, and that their privileges were in fact updated in Late Antiquity ([Oikonomides, 2002](#); [Zimmermann, 2014](#)), in the Sasanian Empire the state strictly supervised production and output ([Christensen, 1936](#)). With the arrival of Islam individual entrepreneurs gained a much firmer hold on their own production processes, as discussed by [Bessard \(2020\)](#).

It is, however, known that, once the almost total dependence on natron as glass flux came to an end in the 8th-9th century CE, the widespread availability of plants capable of producing glass-worthy ashes in the Mediterranean basin and the European continent led to the multiplication of local glassmaking centres, probably as early as the 8th-9th century in Carolingian Europe ([Barfod et al., 2024](#); [Ma et al., 2023](#); [Van Wersch et al., 2016](#); see also [Velde and Motteau, 2013](#); [Wedepohl, 2005](#)). The use of local plant ashes as a glass flux seems to have led to consolidated local glassmaking industries in al-Andalus by the 10th century, if not earlier ([Duckworth and Govantes-Edwards, 2020](#)).

As such, if we admit that a 'marginal' glass industry was in operation in the periphery of Natronland, it is not implausible to think that it was organised along similarly local/regional lines. This is impossible to prove with the evidence currently available, but a number of variables would seem to point that way. First, the use of local plants which are found in abundance across Egypt, which would make the state's task of monitoring/taxing their use much harder than with natron, which, as far as glass is concerned at least, came from one or, at most, two well-defined areas. It is known that natron was taxed in Egypt during the Ptolemaic ([Heichelheim, 1958](#)) and the Abbasid periods ([Décobert, 2003](#)), and although there is no evidence for this also being the case during the Roman period, the possibility should not be ruled out. Natron is a valuable resource unlikely to have remained below the radar of fiscal authorities for too long, and it may be important to note that natron is listed in Diocletian's Price Edict of 301 CE ([Crawford and Reynolds, 1979](#)), if that is what the "A[phronitri ...]" mentioned right after soap is referring to, as seems likely. Finally, although the matter of the scale of primary production, or, in other words, of the continent-wide demand for 'fresh' glass, remains highly speculative, the demand for IPAN glass seems to have undergone, comparatively, much more violent ebbs and flows than that of natron glass, and this kind of elasticity is better served by smaller production units with lower overheads and risk than the sort of industrial facilities operated by the primary suppliers of natron glass.

It is also important to note that, at the consumer level, the coexistence was not limited to natron and IPAN glass, but also included imports of glass from outside Natronland, presumably in the form of finished items. This is, for instance, the case with the Mesopotamian/Sasanian glasses reported by [Al-Bashaireh et al. \(2016\)](#) in Byzantine northeast Jordan and likely some of the samples reported by [Cosyns et al. \(2021\)](#) from Kouklia (Cyprus), although some of these may have been mixed with natron glass. The IPAN glasses found in Sedeinga and rescue excavation beyond the 4th cataract of the Nile in northern Sudan, alongside even Indian glass, clearly imported via the Indian Ocean trade network, may present an analogous case south of Natronland ([Rosenow and Rehren, forthcoming](#)). The presence of such eastern plant-ash glass in Natronland reflects the wide movement of glass artefacts across cultural boundaries, without indicating the production or working of such plant-ash glass in the west. Such 'bleeding' of occasional glass objects of

foreign compositions across the established boundaries of natron glass production and consumption is to be expected, particularly for sites near the interface of Natronland and Mesopotamia. Extreme cases for the dislocation of glass across established compositional domains include the discovery of both Levantine and Sasanian glass in China, and even Japan and Korea, at a time when the glass technologies in the region were based on lead-silica or potash-silica compositions (Dussubieux, 2016; Gan et al., 2021).

3.4. Technological change

Over the last two decades or so, much research has been devoted to defining the process of technological change that resulted in the substitution of plant ash for natron as a glass flux, which is typically explained as the result of an absolute reduction in the volume of natron available or the diversion of production to other uses. This model of explanation assumes that the natron used in glassmaking was sourced from one or two locations (Wadi Natrun and al-Barnuj, both in Egypt), making for a very inelastic supply (Shortland et al., 2006).

The chronology of the technological changeover is of great interest, and speaks of a gradual process, rather than a sudden shock (Freestone, 2021, 2023). Even before the earliest productions of glass fluxed with plant ash alone, by the 8th century, there seems to be a reduction in the soda contents in glass by as much as 20–25 % relative (Henderson, 2002; Freestone et al., 2000), strongly suggesting that natron was indeed becoming harder to come by. This change is perceived first in the Levant, which lay farther from the sources of natron (Shortland et al., 2006), and where the phenomenon is coupled with a significant influx of glass from Egypt (Phelps et al., 2016), where natron glass persists for longer. Thus, *true* plant ash glass emerges in Syria-Palestine in the late 8th century (Phelps, 2018) and in Egypt only in the 9th century (Schibille et al., 2019). This impression is only increased by the findings of experimental work by Jackson et al. (2018), which indicate that the amount of natron needed to produce glass when it was the only flux was much larger than anticipated.

Is it possible that whatever processes ultimately triggered the adoption of plant ash as the only flux started even earlier than hitherto believed, potentially opening a gap in the market for IPAN glass to fill. A firm answer to this question is hampered by one unknown variable too many. Because, how to quantify what was 'enough' glass? In other words, how much fresh glass was needed every year to keep up with demand? Demand is not only affected by factors such as population size and purchasing power, but by other imponderables such as loss rate and changing civic attitudes to public space. Notably, the latter must have made the enormous amount of window glass in Roman public buildings fair game for remelting and presumably reducing, at least temporarily and locally, the need for fresh glass.

At any rate, the chemical data reflect remarkable homogeneity in IPAN glasses, especially for such a long timespan. Although some differences have been pointed out, especially in terms of lime, phosphorus and, perhaps, barium, they are not particularly dramatic. The differences in barium are likely in relation to MnO contents: barium is a known minor component of some manganese ores, and barium and manganese oxides are strongly correlated in IPAN glasses ($R: 0.94$). Thinking about these glasses as different iterations of the same core tradition does not feel like a stretch (while thinking about a sequence of exnovations and innovations that keep hitting roughly the same spot does), not unlike Levantine natron glasses, which remain recognisable throughout despite some changes in composition over time. The silica source-discriminant oxides and elements point to the use of similar sands (perhaps in inland Egypt?) and the correlation between flux-discriminant oxides also remains notably consistent. The weak point of the argument is the comparatively small number of samples that we possess for the period between the 2nd and 6th centuries, when this alleged glass tradition appears to have had less projection outside of Egypt. Rather than being related to technological practices, however,

this is likely the result of broader macroeconomic conditions; the geographical projection of these glasses seems to have responded to external demand. As such, although we can try to establish thresholds to distinguish between compositional groups with defined chronologies, this runs the risk, at least for the purposes of this paper, of artificially creating analytical categories that unwarrantedly break up a more fluid reality (which is not to say that compositional differences should be dismissed as unimportant). Similarly, the identification of subtypes (e.g. low- and high-Mn late IPAN glass, suggesting that some of these glasses contain some Mn-rich additive, likely for colouring purposes) would only indicate that the same production tradition could accommodate slightly different practices to meet different demands.

It is, however, recognised that it is possible that early and middle/late IPAN glasses are the reflection of two different traditions and industries, the former of which was short-lived (unless it can be shown that it was continued in the form of strongly-coloured non-blown objects after the demise of emerald-green glass); and the latter emerging only, based on the evidence, in the 4th century. It is fair to say that the authors of this article are not completely in agreement about all the variables involved, although the 'continuity hypothesis' has been given more prevalence in the final manuscript. However, even if the 'two traditions' hypothesis is the correct one, the similarities between these two strands of glass would be too many and too close not to be examined in terms of technological transmission.

Traditional narratives relate, probably correctly, the adoption of plant-ash fluxes in the Levant and Egypt in the 8th and 9th centuries to the continuous use of this technology east of the Euphrates. However, this must not be held to mean that glassmakers west of the Euphrates were unaware of the fluxing properties of this material. Preindustrial craftspeople were deeply knowledgeable about their own trades, and it must be recalled that the properties shared by natron and plant ashes are manifested in things other than glassmaking (e.g. soapmaking), and the continuous production of IPAN glass throughout the period shows that the knowledge was there. Therefore, it seems plausible to think that the adoption of east-of-the-Euphrates- rather than IPAN glass-inspired technology had more to do with the restricted availability of natron for glassmaking than with a technological choice. In fact, the adoption of this technology was far from frictionless, as demonstrated by the failure to melt of the Bet She'arim slab, likely caused by the combination of lime-rich plant ash and sands, resulting in an excess of lime (Freestone and Gorin-Rosen, 1999), and, perhaps, a more or less long process of experimentation suggested by Henderson et al. (2004) in Raqqa. How the technological transfer occurred remains unclear, but it may have travelled together with that of local craftspeople in the newly-formed Umayyad and later Abbasid caliphates, either in the context of state-sponsored projects (Northedge et al., 2014) or of itinerant glassmakers, which are documented in Late Antiquity as well as the Early Middle Ages (Zimmermann, 2014). It is important that we try to define the institutional setting in which innovation occurs. In the Germanic kingdoms of the West craftspeople were slaves or at least legal dependents with clearly defined tasks to fulfil in the manorial economy, so it would be easy to think that they had no motivation or pressure to innovate when they could get their glass from the 'recycling bin' (Zimmermann, 2023). But the fact is that they did, probably even sooner than in the eastern Mediterranean, where all the evidence suggests that the mainstream glass industry held on to natron for as long as it could. In this instance, perhaps, distance and institutional autonomy from the production structures and sources of natron glass simply sped innovation along.

4. Conclusions

This paper has examined the composition, distribution, and potential technological and institutional implications of glasses made, at least partially, with plant ash in Natronland. The compositional data suggests that, although there is a degree of compositional variation over time,

IPAN glasses can be argued to represent a single and separate technological tradition, distinct from the contemporary Mesopotamian/Sasanian glass. Like Levantine glasses, there are some shifts in a number of compositional parameters over time, but the core of the technology remains recognisable throughout. From a compositional perspective, the most outstanding feature of these glasses is the mix of mineral- and plant-based fluxes, not only because of the deep knowledge it betrays about the physical properties of different materials, but also because it is one of the most stable compositional characteristics of these glasses. Although some variables such as their phosphorus contents change, the potash plus magnesia to soda ratio stays much the same for nearly a millennium (0.21 in early IPAN; 0.23 in mid IPAN; and 0.20 in late IPAN). The former phenomenon could be a by-product of the use of different plant species or of some of the variables that affect the composition of these, while the latter speaks of a well-controlled process, and this in turn suggests that this was a technological *choice*, not an expediency driven by circumstance. Other compositional variables (silica-source discriminants such as titanium, zirconium, and lime) strongly suggest an Egyptian production, perhaps situated inland. This could be located in Upper Egypt and northern Sudan, as the distribution of known finds for the long period between the 2nd and 6th century, when IPAN glass appears to have been flushed out of mainstream markets by natron glass, seems to indicate. The weakest point of this argument is perhaps that the known examples for this lengthy period are indeed few. In the early stage, much of the glass that left the production area was strongly-coloured specialised glass, perhaps aided by the afterglow of the Hellenistic and early Roman preference for such glasses. The potential connection of wares such as the emerald green glasses and other strongly-coloured (including black-looking) glasses, many of which also present features that suggest the use of plant-ash fluxes, is worth more intensive research; its nature as a 'speciality glass' could suggest an intentional production within the canon of similar colour-specialised glasses (see also [Rehren and Cholakova, 2024](#)).

In the suggested Upper Egyptian/Sudanese production area, on the other hand, this glass is found to be used in everyday forms, and the logic of this may rest in greater distance from the natron sources, which made it more economical or convenient to mix the natron salts with plant ash, leading to an industry of some local or regional importance.

How this putative branch of the wider glass industry was organised is impossible to say at this stage. Even most aspects of the operation of the much better-known natron glass sector are still poorly understood, particularly in terms of what specific mechanisms were mobilised to commercialise the glass. But that these parallel industries were very different in outlook appears to be beyond doubt. While the production of natron glass relied on large-scale facilities that must have demanded considerable investment, the sharp differences in the visibility of IPAN glass outside the suggested production area points to much smaller production units, able to contract and expand more flexibly in response to external economic conditions or opportunities.

What made IPAN glass become so much more conspicuous in Mediterranean markets in the 6th and 7th centuries also remains a matter of speculation. However, by those centuries the reduction of the soda to silica ratios in Levantine glasses is noticeable, and soon afterwards there was an unprecedented influx of Egyptian glass into the Levant, both of which phenomena are likely related to the gradual reduction of the natron available to glassmakers there in the run-up to the substitution of plant-ash glass for natron glass. It is, therefore, not implausible to link the growth of IPAN glass to the same underlying causes. In fact, if we stretch the argument further, it is not unthinkable that when the ultimate changeover took place, east-of-the-Euphrates technologies were relatively easily adopted (though not without a glitch or two), because of pre-existing experience with IPAN glass, a consequence of the increasing scarcity of natron as over a number of centuries.

CRediT authorship contribution statement

David J. Govantes-Edwards: Writing – original draft, Formal analysis, Data curation. **Peter Cosyns:** Writing – review & editing, Formal analysis, Data curation. **Patrick Degryse:** Writing – review & editing, Formal analysis, Data curation. **Chloe Duckworth:** Writing – review & editing, Formal analysis, Data curation. **Ian C. Freestone:** Writing – review & editing, Formal analysis, Data curation. **Marcel Frenken:** Writing – review & editing, Formal analysis, Data curation. **Caroline Jackson:** Writing – review & editing, Formal analysis, Data curation. **Artemios Oikonomou:** Writing – review & editing, Formal analysis, Data curation. **Thilo Rehren:** Writing – review & editing, Formal analysis, Data curation. **Jose Alberto Retamosa:** Writing – review & editing, Formal analysis, Data curation. **Daniela Rosenow:** Writing – review & editing, Formal analysis, Data curation. **Andrew Shortland:** Writing – review & editing, Formal analysis, Data curation. **Martin Zimmermann:** Writing – review & editing, Formal analysis, Data curation.

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Appendix A. Supplementary data

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References

- Al-Bashaireh, K., Al-Housan, A.-Q., Freestone, I., Al-Mustafa, S., 2016. Composition of Byzantine glasses from Umm el-Jimal, northeast Jordan: insights into glass origin and recycling. *J. Cult. Herit.* 21, 809–818. <https://doi.org/10.1016/j.culher.2016.04.008>.
- Ali, N., Abd-Allah, R., 2015. The authentication and characterisation of glass objects excavated from Tell es-Sukhnah, Jordan. *Mediterranean Archaeology and Archaeometry* 15 (1), 39–50. <https://doi.org/10.5281/zenodo.15003>.
- Arancibia, A., 2014. Memoria final de la A. A. P. En Los Entornos Del Guadalmedina Y Renfe De Las Líneas 1 Y 2 Del Metro De Málaga, pp. 2010–2014. Unpublished excavation report.
- Arletti, R., Fiori, C., Vandini, M., 2010. A study of glass tesserae from mosaics in the monasteries of Daphni and Hosios Loukas (Greece). *Archaeometry* 52 (5), 796–815. <https://doi.org/10.1111/j.1475-4754.2009.00504.x>.
- Ashtor, E., Cevdali, G., 1983. Levantine alkali ashes and European industries. *J. Eur. Econ. Hist.* 12, 475–522. <https://doi.org/10.1016/j.jas.2006.01.004>.
- Barfod, G.H., Feveile, L.L., Sindbæk, S.M., 2024. The emperor's new glass: the introduction of Carolingian wood ash glass in North Sea trade. *Archaeometry* 66, 534–551. <https://doi.org/10.1111/arcn.12968>.
- Barkoudah, Y., Henderson, J., 2006. Plant ashes from Syria and the manufacture of ancient glass: Ethnographic and scientific aspects. *J. Glass Stud.* 48, 297–321.
- Bessard, F., 2020. Caliphs and Merchants: Cities and Economies of Power in the Near East. Oxford University Press, Oxford, pp. 700–950.
- Boschetti, C., Henderson, J., Evans, J., Leonelli, C., 2016. Mosaic tesserae from Italy and the production of Mediterranean coloured glass (4th century BCE–4th century CE). Part I: chemical composition. *J. Archaeol. Sci.: Reports* 7, 303–311. <https://doi.org/10.1016/j.jasrep.2016.05.006>.
- Brill, R., 1999. Chemical Analyses of Early Glasses. The Corning Museum of Glass, Corning, NY vols. 1 and 2.
- Carmona, N., Villegas, M.A., Jiménez, P., Navarro, J., García-Heras, M., 2009. Islamic glasses from Al-Andalus. Characterisation of materials from a Murcian workshop (12th century AD, Spain). *J. Cult. Herit.* 10, 439–445. <https://doi.org/10.1016/j.culher.2008.12.005>.
- Ceglia, A., Cosyns, P., Nys, K., Terryn, H., Thienpont, H., Meulebroeck, W., 2015. Late antique glass distribution and consumption in Cyprus: a chemical study. *J. Archaeol. Sci.* 61, 213–222. <https://doi.org/10.1016/j.jas.2015.06.009>.
- Cheng, Q., Rehren, Th., Ogutu, J., Carter, R.A., 2024. Glass ornaments in the late Islamic period: composition of glass bangles from northern Qatar. *Archaeol. Anthropol. Sci.* 16, <https://doi.org/10.1007/s12520-023-01903-4>.
- Cholakova, A., Rehren, Th., Freestone, I., 2016. Compositional identification of 6th c. AD glass from the lower Danube. *J. Archaeol. Sci.: Reports* 7, 625–632. <https://doi.org/10.1016/j.jasrep.2015.08.009>.
- Christensen, A., 1936. *L'Idan Sous Les Sassanides*. Levin & Munksgaard, Copenhagen.
- Cosyns, P., 2011. The Production, Distribution and Consumption of Black Glass in the Roman Empire During the 1st–5th Century AD. an Archaeological, Archaeometric and Historical Approach. Free University Brussels. Unpublished PhD dissertation.
- Cosyns, P., Ceglia, A., Thienpont, H., Wartburg, M.L., 2021. A late antique glass workshop at the Aphroditē sanctuary of Palaepaphos, Kouklia (Cyprus). In: Sevidik, O. (Ed.), *Annales Du 21e Congrès De L'Association Internationale Pour L'Histoire Du Verre* (Istanbul 2018). AIHV, Istanbul, pp. 291–306.
- Crawford, M.H., Reynolds, J.M., 1979. The aezani copy of the prices edict. *Z. Papyrol. Epigr.* 34, 163–210.
- de J., Juan, Schibille, N., 2017. Glass import and production in Hispania during the early medieval period: the glass from Ciudad de Vascos (Toledo). *PLoS One* 12, 1–19. <https://doi.org/10.1371/journal.pone.0182129>.
- Déobert, C., 2003. Le natron égyptien au Moyen-Age. In: Foy, D., Nenna, M.-D. (Eds.), *Échanges Et Commerce Du Verre Dans La Monde Antique: Actes Du Colloque De L'Association Française Pour L'Archéologie Du Verre, Aix-en-Provence Et Marseille*. Éditions Monique Mergoil, Montagnac, pp. 125–127.
- de Juan, J., Vigil-Escalera, A., Cáceres, Y., Schibille, N., 2019. Changes in the supply of eastern Mediterranean glasses to Visigothic Spain. *J. Archaeol. Sci.* 107, 23–31. <https://doi.org/10.1016/j.jas.2019.04.006>.
- Degryse, P., 2014. Glass Making in the Greco-Roman World: Results of the ARCHGLASS Project, 4. Leuven University Press. Studies in Archaeological Sciences, Leuven.
- Drauschke, J., Greiff, S., 2010. Chemical aspects of Byzantine glass from Caričin Grad/Iustiniana Prima (Serbia). In: Drauschke, J., Keller, D. (Eds.), *Glass in Byzantium – Production, Usage, Analyses*. Verlag des Römisch-Germanischen Zentralmuseums, Mainz, pp. 25–45.
- Duckworth, C., Córdoba de la Llave, R., Faber, E.W., Govantes-Edwards, D., Henderson, J., 2015. Electron microprobe analysis of 9th–12th century Islamic glass from Córdoba, Spain. *Archaeometry* 57, 27–50. <https://doi.org/10.1111/arcn.12079>.
- Duckworth, C., Govantes-Edwards, D., 2020. Producción y tecnología del vidrio en al-Andalus. In: Delgado, M.M., Pérez-Aguilar, L.G. (Eds.), *Economía Y Trabajo. Las Bases Materiales De La Vida En al-Andalus*. Ediciones Alfár, Seville, pp. 235–262.
- Dussubieux, L., 2016. Potash glass: a view from South and Southeast Asia". In: Gan, F. (Ed.), *Recent Progress of Scientific Research on Ancient Glass and Glazes*. Series on Archaeology and History of Science in China (Book 2). World Scientific Publishing, Singapore, pp. 95–111.
- Foy, D., 1995. In: Foy, D. (Ed.), *Le Verre De La Fin Du IVe Au VIIIe Siècle En France Méditerranéenne. Premier Essai De typologie-chronologie*. Le verre de l'Antiquité Tardive et du Haut Moyen Age. Typologie-Chronologie-Diffusion, Musée Archéologique Départemental du Val d'Oise, Guiry-en-Vexin, pp. 187–242.
- Foy, D., Picon, M., Vichy, M., Thirion-Merle, V., 2003. Caractérisation des verres de l'Antiquité tardive en Méditerranée occidentale: l'émergence de nouveaux courants commerciaux. In: Foy, D., Nenna, M.-D. (Eds.), *Échanges Et Commerce Du Verre Dans Le Monde Antique. Actes Du Colloque De L'Afiv. Aix-en-Provence – Marseille*, 2001. Monique Mergoil, Montagnac, pp. 41–86.
- Freestone, I., 2015. The recycling and reuse of Roman glass: analytical approaches. *J. Glass Stud.* 57, 29–40.
- Freestone, I., 2021. Glass production in the first millennium CE: a compositional perspective. In: Klimscha, F. (Ed.), *Ancient Glass and Glass Production*. Berlin Studies of the Ancient World 67. Topoi, Berlin, pp. 243–262.
- Freestone, I., 2023. The archaeometry of glass. In: Pollard, M., Armitage, R.A., Makarewicz, C.A. (Eds.), *Handbook of Archaeological Sciences*, second ed. John Wiley & Sons, London, pp. 885–910. <https://doi.org/10.1002/9781119592112.ch44>.
- Freestone, I., Gorin-Rosen, Y., 1999. The great glass slab at Bet She'Arim, Israel: an early Islamic glassmaking experiment? *J. Glass Stud.* 41, 105–116.
- Freestone, I., Gorin-Rosen, Y., Hughes, M.J., 2000. Primary glass from Israel and the production of glass in Late Antiquity and the early Islamic Period. In: Nenna, M.-D. (Ed.), *La Route Du Verre: Ateliers Primaires Et Secondaires Du Second Millénaire Av. J.-C. au Moyen Age*. Maison de L'Orient Méditerranéen, Lyon, pp. 65–83.
- Freestone, I., Leslie, K.A., Thirlwall, M., Gorin-Rosen, Y., 2003. Strontium isotopes in the investigation of early glass production: Byzantine and early Islamic glass from the Near East. *Archaeometry* 45, 19–32. <https://doi.org/10.1111/1475-4754.00094>.
- Freestone, I., Hughes, M.J., Stapleton, C., 2008a. The composition and production of Anglo-Saxon glass. In: Marzinzik, S. (Ed.), *Catalogue of Anglo-Saxon Glass in the British Museum*, 167. British Museum Research Publication, London, pp. 29–46.
- Freestone, I., Jackson-Tal, R.E., Tal, O., 2008b. Raw glass and the production of glass vessels at late Byzantine apollonia-arsuf, Israel. *J. Glass Stud.* 50, 67–80.
- Gan, F., Li, H., Hou, L. (Eds.), 2021. Development History of Ancient Chinese Glass Technology. World Scientific, Singapore.
- Gallo, F., Silvestri, A., Molin, G., 2013. Glass from the archaeological museum of Adria (North-East Italy): new insights into early Roman production technologies. *J. Archaeol. Sci.* 40, 2589–2605. <https://doi.org/10.1016/j.jas.2013.01.017>.
- Glozzio, E., Santagostino Barbone, A., D'Acapito, F., 2013. Waste glass, vessels and window-panes from Thamusida (Morocco): grouping natron-based blue-green and colourless Roman glasses. *Archaeometry* 55, 609–639. <https://doi.org/10.1111/j.1475-4754.2012.00696.x>.
- Govantes-Edwards, D., Velo, A., Hernández-Robles, A., Gonzáles-Ballesteros, J.M., Duckworth, C., 2024. The glass from the arrabal of Arraxaca (Murcia, 12th–13th centuries). *Archaeol. Anthropol. Sci.* 16, 1–20. <https://doi.org/10.1007/s12520-024-02066-6>.
- Govantes-Edwards, D., Fernández, A., Duckworth, C., 2025. The Atlantic road. Late Antique/early medieval glass trade in the Iberian North-West. *Mediev. Archaeol.* 69, 1–34.
- Heichelheim, F.M., 1958. An ancient economic history: from the Palaeolithic age to the migrations of the Germanic, Slavic and Arabic nations. Revised and Complete English Translation by J. Stevens. A. W. Sijthoff, Leiden.
- Henderson, J., 1996. Scientific analysis of selected Fishbourne vessel glass and its archaeological interpretation. In: Cunliffe, B.W., Down, A.G., Rudkin, D.J. (Eds.), *Chichester Excavations IX, Excavations at Fishbourne 1969–1988*. Chichester District Council, Chichester, pp. 189–192.
- Henderson, J., 2002. Tradition and experiment in first millennium AD glass production. The emergence of early Islamic glass technology in late antiquity. *Accounts of Chemical Research* 35, 594–602.
- Henderson, J., McLoughlin, S.D., McPhail, D.S., 2004. Radical changes in Islamic glass technology: evidence for conservatism and experimentation with new glass recipes from early and middle Islamic Raqqa, Syria. *Archaeometry* 46, 439–468.
- Jackson, C., 1996. From Roman to Early Medieval Glasses: Many Happy Returns or a New Birth, 1995. *Annales du 13 Congrès de l'Association Internationale pour l'Histoire Du Verre*, pp. 289–302.
- Jackson, C., Cottam, S., 2015. A green thought in a green shade'; Compositional and typological observations concerning the production of emerald green glass vessels in the 1st century AD. *J. Archaeol. Sci.* 61, 139–148. <https://doi.org/10.1016/j.jas.2015.05.004>.
- Jackson, C., Paynter, S., Nenna, M.-D., Degryse, P., 2018. Glassmaking using natron from el-Barnugi (Egypt); Pliny and the Roman glass industry. *Archaeol. Anthropol. Sci.* 10, 1179–1191. <https://doi.org/10.1007/s12520-016-0447-4>.
- Kaparov, M., Oikonomou, A., 2022. Mycenaean through Hellenistic glass in Greece: where have we got to? *Archaeol. Anthropol. Sci.* 14. <https://doi.org/10.1007/s12520-022-01558-7>.
- Lilyquist, C., Brill, R.H., 1993. *Studies in Early Egyptian Glass*. The Metropolitan Museum of Art, New York.
- Lucas, V., 2022. Why Recycle Glass? The Answer is Clear? Glass Recycling in the 7th–10th Centuries in England. Newcastle University. PhD Dissertation.
- Ma, H., Henderson, J., Sablerolles, Y., Chenery, S., Evans, J., 2023. Early Medieval Glass Production in the Netherlands. A Chemical and Isotopic Investigation. Cultural Heritage Agency of the Netherlands Amersfoort.

- McCormick, M., 2001. Origins of the European Economy. Communications and Commerce, A.D. Cambridge University Press, Cambridge, pp. 300–900.
- Mirti, P., Pace, M., Pegro Ponzi, M.N., Aceto, M., 2008. ICP-MS analysis of glass fragments of Parthian and Sasanian epoch from Seleucia and Veh Ardasir (Central Iraq). *Archaeometry* 50, 429–450. <https://doi.org/10.1111/j.1475-4754.2007.00344.x>.
- Moretti, C., Gratuze, B., 2000. I Vetri Rossi Al Rame Confront Di Analisi E Ricette. *Annales du 14e Congrès de l'Association Internationale pour l'Histoire du Verre*, pp. 227–232.
- Nenna, M.-D., 2015. Primary glass workshops in Graeco-Roman Egypt: preliminary report on the excavations of the site of Beni Salama, Wadi Natrun (2003, 2005–9). In: Bailey, J., Jackson, C., Freestone, I. (Eds.), *Glass of the Roman World*. Oxbow, Oxford, pp. 1–22.
- Nenna, M.-D., Gratuze, B., 2009. Etude diachronique des compositions de verres employés dans la vases mosaïque: résultats préliminaires. In: Janssens, K., Degryse, P., Cosyns, P., Caen, J., Vant' dack, L. (Eds.), *Proceedings of the Annales Du 17e Congrès De L'Association Internationale Pour L'Histoire Du Verre*. University Press, Antwerp, Antwerp, pp. 199–205.
- Neri, E., Verita, M., 2013. Glass and metal analyses of gold leaf tesserae from 1st to 9th century mosaics. A contribution to technological and chronological knowledge. *J. Archaeol. Sci.* 40, 4596–4606. <https://doi.org/10.1016/j.jas.2013.07.017>.
- Northedge, A., Abdellatif, R., Gonnella, J., 2014. 'Askar a-Mu'asim: the central city of Samarra. *Beiträge zur Islamischen Kunst und Archäologie: Jahrbuch der Ernst-Herzfeld-Gesellschaft* 4, 38–62.
- Oikonomides, N., 2002. The role of the Byzantine state in the economy. In: Laiou, A.E. (Ed.), *The Economic History of Byzantium: from the Seventh Through the Fifteenth Century*, 3, pp. 973–1058. Washington DC, Dumbarton Oaks.
- Oikonomou, A., Rehren, Th., Fiolitiaki, A., 2021. An early Byzantine glass workshop at Argyroupolis, Crete: insights into complex glass supply networks. *J. Archaeol. Sci.: Reports* 35, 1–12. <https://doi.org/10.1016/j.jasrep.2020.102766>.
- Palomar, T., Garcia-Heras, M., Sabio, R., Rincón, J.-M., Villegas, M.-A., 2012. Composition, preservation and production technology of Augusta Emerita Roman glasses from the first to the sixth century AD. *Mediterranean Archaeology and Archaeometry* 12 (2), 193–211.
- Paynter, S., 2008. Experiments in the reconstruction of Roman wood-fired glassworking furnaces: waste products and their formation processes. *J. Glass Stud.* 50, 271–290.
- Paynter, S., Jackson, C., 2016. Re-used Roman rubbish: a thousand years of recycling glass. *European Journal of Postclassical Studies* 6, 31–52.
- Paynter, S., Kearns, T., 2011. *West Clacton Reservoir, Great Bentley, Essex: Analysis of Glass Tesserae*. English Heritage Research Department Research Series, pp. 44–2011.
- Phelps, M., 2018. Glass supply and trade in early Islamic Ramla: an investigation of the plant ash glass. In: Rosenow, D., Phelps, M., Meek, A., Freestone, I. (Eds.), *Things that Travelled: Mediterranean Glass in the First Millennium AD*. UCL Press, London, pp. 236–282.
- Phelps, M., Freestone, I., Gorin-Rosen, Y., Gratuze, B., 2016. Natron glass production and supply in the late antique and early medieval Near East: the effect of the Byzantine-Islamic transition. *J. Archaeol. Sci.* 75, 57–71. <https://doi.org/10.1016/j.jas.2016.08.006>.
- Picon, M., Thirion-Merle, V., Vichy, M., 2008. Les verres au natron et les verres aux cendres du Wadi Natrun (Egypte). *Bulletin de l'Association Française pour l'Archéologie du Verre* 18, 36–41.
- Rehren, Th., Brüggler, M., 2015. Composition and production of late antique glass bowls type Helle. *J. Archaeol. Sci.: Reports* 3, 171–180. <https://doi.org/10.1016/j.jasrep.2015.05.021>.
- Rehren, Th., Cholakova, A., 2024. Parvus inter pares – HIT glass and its relationship to HIMT: an ongoing discussion. In: Commendré, I., Fontaine, S., Fünfschilling, S., Mach, J., Munier, C. (Eds.), *MARE VITREUM. Mélanges Offerts À Danièle Foy. Mergoïl, Dremil-Lafage*, pp. 243–263.
- Rehren, Th., Freestone, I., 2015. Ancient glass: from kaleidoscope to crystal ball. *J. Archaeol. Sci.* 56, 233–241. <https://doi.org/10.1016/j.jas.2015.02.021>.
- Rehren, Th., Rosenow, D., 2020. Three millennia of Egyptian glassmaking. In: Duckworth, C., Cuénod, A., Mattingly, D. (Eds.), *Mobile Technologies in the Ancient Sahara and Beyond*. Cambridge University Press, Cambridge, pp. 423–450.
- Rosenow, D., Rehren, Th., 2014. Herding cats – Roman to late Antique glass groups from Bubastis. *J. Archaeol. Sci.* 49, 170–184. <https://doi.org/10.1016/j.jas.2014.04.025>.
- Rosenow, D., Rehren, Th., 2018. A view from the south: Roman and late Antique glass from Armant, Upper Egypt. In: Drauschke, J., Keller, D. (Eds.), *Glass in Byzantium – Production, Usage, Analyses*. De Gruyter, Berlin, pp. 283–323.
- Schibille, N., 2022. Islamic glass in the making. Chronological and Geographical Dimensions. Leuven University Press, Leuven. <https://doi.org/10.2307/j.ctv2bhfhhht>.
- Schibille, N., Meek, A., Tobias, B., Entwistle, C., Avisseau-Brousset, M., Da Mota, H., Gratuze, B., 2016. Comprehensive chemical characterisation of Byzantine glass weights. *PLoS One* 11, 1–26. <https://doi.org/10.1371/journal.pone.0168289>.
- Schibille, N., Meek, A., Wypyski, M.T., Kröger, J., Rosser-Owen, M., Haddon, R.W., 2018. The glass walls of Samarra (Iraq): ninth-century Abbasid glass production and imports. *PLoS One* 13, 1–16. <https://doi.org/10.1371/journal.pone.0201749>.
- Schibille, N., Gratuze, B., Ollivier, E., Blondeau, E., 2019. Chronology of early Islamic glass compositions from Egypt. *J. Archaeol. Sci.* 104, 10–18. <https://doi.org/10.1016/j.jas.2019.02.001>.
- Schibille, N., Lankton, J.W., Gratuze, B., 2022. Compositions of early Islamic glass along the Iranian Silk Road. *Geochemistry* 82. <https://doi.org/10.1016/j.chemer.2022.125903>.
- Schibille, N., Klesner, C., Neuville, D.R., Stark, S., Torgoev, A.I., Mirzaakhmedov, S.J., 2024. Geochemical variations in early Islamic glass finds from Bukhara (Uzbekistan). *Geochemistry* 84. <https://doi.org/10.1016/j.chemer.2024.126078>.
- Shortland, A., 2004. Evaporites of the Wadi Natrun: seasonal and annual variation and its implication for ancient exploitation. *Archaeometry* 46, 497–516. <https://doi.org/10.1111/j.1475-4754.2004.00170.x>.
- Shortland, A., Schachner, L., Freestone, I., Tite, M., 2006. Natron as flux in the early vitreous materials industry: sources, beginnings and reasons for decline. *J. Archaeol. Sci.* 33, 521–530. <https://doi.org/10.1016/j.jas.2005.09.011>.
- Shortland, A., Eremin, K., Degryse, P., Walton, M., 2018. The analysis of Late Bronze Age glass from Nuzi and the question of the origin of glass-making. *Archaeometry* 60, 764–783. <https://doi.org/10.1111/arcm.12332>.
- Silvestri, A., 2008. The coloured glass from Iulia Felix. *J. Archaeol. Sci.* 35, 1489–1501. <https://doi.org/10.1016/j.jas.2007.10.014>.
- Silvestri, A., Molin, G., Salviolo, G., 2008. The colourless glass of Iulia Felix. *J. Archaeol. Sci.* 35, 331–341. <https://doi.org/10.1111/j.1475-4754.2005.00233.x>.
- Simpson, St J., 2014. Sasanian glass. An overview. In: Keller, D., Price, J., Jackson, C. (Eds.), *Neighbours and Successors of Rome: Glass Production and Use in Europe and the Middle East in the Later 1st Millennium AD*. Oxbow, Oxford, pp. 200–231. <https://doi.org/10.2307/j.ctvh1dq24.24>.
- Siu, I., Henderson, J., Faber, E., 2017. The production and circulation of Carthaginian glass under the rule of the Romans and the Vandals (fourth to sixth century AD): a chemical investigation. *Archaeometry* 59, 255–273. <https://doi.org/10.1111/arcm.12252>.
- Smith, R.W., 1963. Archaeological evaluation of analyses of ancient glass. In: Matson, F. R., Rindone, G.E. (Eds.), *Advances in Glass Technology*. Plenum Press, New York, pp. 283–290.
- Taylor, M., Hill, D., 2008. Experiments in the reconstruction of Roman wood-fired glassworking furnaces. *J. Glass Stud.* 50, 248–270.
- Tite, M.S., Shortland, A., Maniatis, Y., Kavoussanaki, D., Harris, S.A., 2006. The composition of the soda-rich and mixed alkali plant ashes used in the production of glass. *J. Archaeol. Sci.* 33, 1284–1292. <https://doi.org/10.1016/j.jas.2006.01.004>.
- Van der Linden, V., Cosyns, P., Schalm, O., Cagno, S., Nys, K., Janssens, K., Nowak, A., Wagner, E., Bulska, E., 2009. Deeply coloured and black glass in the northern provinces of the Roman empire: differences and similarities in chemical composition before and after 150 AD. *Archaeometry* 51/5, 822–844. <https://doi.org/10.1111/j.1475-4754.2008.00434.x>.
- Van Wersch, L., Loisel, C., Mathis, F., Strivay, D., Bully, S., 2016. Analyses of early medieval stained window glass from the monastery of Baume-Les-Messieurs (Jura, France). *Archaeometry* 58 (6), 930–946. <https://doi.org/10.1111/arcm.12207>.
- Velde, B., Motteau, J., 2013. Glass compositions of the Merovingian period in Western Europe. In: Janssens, K. (Ed.), *Modern Methods for Analysing Archaeological and Historical Glass*. John Wiley & Sons, London, pp. 387–397. <https://doi.org/10.1002/9781118314234.ch18>.
- Vizcaíno, J., 2007. La Presencia Bizantina En Hispania (Siglos VI-VII). La Documentación Arqueológica. Antigüedad Y Cristianismo XXIV. Universidad de Murcia. <https://doi.org/10.6018/ayc. Murcia>.
- Wedepohl, K., 2003. *Glas in Antike und Mittelalter*. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), Stuttgart.
- Wedepohl, K., 2005. Composition of Carolingian glass in Europe. In: *Annales Du 16^e Congrès De L. "Association Internationale pour l'Histoire du Verre*. AIHV, Nottingham, pp. 203–206.
- Wickham, C., 2005. *Framing the Early Middle Ages*. Oxford University Press, Oxford.
- Wolf, S., Kessler, C.M., Stern, W.B., Gerber, Y., 2005. The composition and manufacture of early medieval coloured window glass from Sion (Valais, Switzerland) - a Roman glass-making tradition or innovative craftsmanship? *Archaeometry* 42 (2), 361–380. <https://doi.org/10.1111/j.1475-4754.2005.00207.x>.
- Zimmermann, M., 2014. *Glashandwerker im Frühmittelalter*. Schmidt-Römhild KG, Lübeck.
- Zimmermann, M., 2023. Neue Forschungen zu Glashandwerkern unter den Karolingern und ihren Nachfolgern (8. bis 10. Jahrhundert). *Frühm. Stud.* 57 (1), 19–53. <https://doi.org/10.1515/fmst-2023-0002>.



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