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Glass working and recycling in Pompeii: new evidence from the landfill of the Sarno Baths (VIII 2, 17–23)

Cristina Boschetti¹ · Guido Furlan² · Nadine Schibille³ · Rubina Raja¹ · Jacopo Bonetto²

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Abstract

Forty-six glass finds, including vessel fragments, windows, one inlay and one indicator of production (moil) excavated in the dump of the Sarno Baths in Pompeii were selected for an interdisciplinary technological, typological and chemical study. The identification of the moil demonstrates that a glassblowing workshop most likely existed in Pompeii, thus putting an end to a long-standing scientific debate. The LA-ICP-MS chemical data show that Roman-Mn base glass predominates, along with few Egyptian natron-type glasses and some plant-ash glass of probable Egyptian origin as well. A large proportion of the analysed glass, including the moil, consists of recycled compositions, suggesting the existence of an efficient system of collection and recycling of glass, which was active even at a time when the city had an abundant supply of fresh glass. The demand for raw glass in Pompeii far exceeded the average demand of other Roman towns, because glass containers were essential for the flourishing perfume industry in Pompeii and Campania. The proximity of the Sarno dump to the perfume district in the south-western part of the city and to the *horrea* of the Sanctuary of Venus suggests the possible location of the glass workshop in this area.

Keywords Pompeii · Glass recycling · Glass working · Roman glass trade · Plant-ash glass · LA-ICP-MS

Introduction

Pompeii, the Roman city buried by the eruption of Mount Vesuvius in 79 CE, offers an exceptional opportunity to study well-dated finds, excavated from sealed contexts. Despite this great research potential, investigations of Vesuvian sites pay little attention to household furnishings and traditionally focus on other topics, namely urbanism, building techniques, architecture and decoration. Glass vessels from Pompeii are no exception. This subject is treated mainly in terms of typology of complete vessels retrieved from the buildings buried by the eruption of 79 CE (Scatozza Hörich 2012). There are only a handful of publications on glass vessels excavated stratigraphically from deposits predating 79 CE (Scatozza Hörich 1987; Cool 2016, 2020) and two relatively recent papers on vessels from non-documented stratigraphies or contexts (De Francesco et al. 2010, 2019). A few articles discussed the chemical composition, microstructure and isotopic signature of glass mosaic tesserae, game counters and ‘sealing-wax red’ vessels from the city (Arletti et al. 2006a, 2006b; Boschetti et al. 2007, 2016, 2017). An interdisciplinary study based on a comparative technological, typology and chemical approach

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of vessels is entirely lacking, so that a more comprehensive picture of the glass economy in Pompeii is missing. The two existing chemical investigations deal with finds from the primary deposits of 79 CE and did not consider the connections between composition, forming technology and typology (Brill 2012; De Francesco et al. 2019). Whether or not glass workshops existed in Pompeii is a matter of debate (Scatozza Höricht 1986, 2012, pp.60–4; Taborelli 1988, 2017, pp.145–6). Infrastructures such as furnaces and glass-working waste have never been identified. The discovery of blocks of raw glass and of one crate with new vessels wrapped in straw in Regio VII was sometimes interpreted as proof of a glass workshop operating in the building (Scatozza Höricht 1986, 2012). It is not possible to prove that the new vessels were made on site, and the blocks of raw glass can be attributed to a commercial rather than an artisanal context. The identification of evidence of glass working in Pompeii would be an outstanding discovery, because archaeological evidence of glass working from Roman Italy is generally scant and completely absent for the first century CE.

Stratigraphic investigations in Pompeii do not help in this sense, because these mainly focussed on intra-mural sites, which are less likely to yield refuse materials related to crafts, including glass-working waste. Liminal spaces, like dumps and landfills, where waste was deposited, have rarely been investigated (Romanazzi and Volontè 1986). For this reason, in our study we addressed glass finds excavated in 2016 from the dump accumulated in the area located immediately outside the city walls, next to the external façade of the building known as Sarno Baths. The stratigraphic and geomorphological investigations revealed that this sector was occupied by marshes formed by the Sarno river (Nicosia et al. 2019; Vignola et al. 2022). This wet environment did not favour the establishment of dwellings or productive activities. During the period between the dramatic earthquake that struck the city in 62 or 63 CE and the eruption of Mount Vesuvius in 79 CE (Andreau 1973), the area was regularly used as dumping site (Furlan et al. 2019; Furlan and Andreatta 2023). In the years preceding the eruption, Pompeii was hit by several earthquakes, which certainly made reconstruction after 62/63 CE difficult (Andreau 1973). This peculiar context offers a privileged vantage point for the study of glass artefacts from Pompeii in the final stages of their life cycle, when they were deposited in the urban waste. Recent studies emphasise the importance of studying the composition of waste products, in order to reconstruct the complex circular dynamics of the Roman urban economy and to question issues such as recycling and reuse (Duckworth and Wilson 2020; Andrade and Raja 2023a, b; Bavuso et al. 2023a, b; Furlan and Andreatta 2023). This approach is particularly important for the study of glass in circulation in the first century CE, when the glass industry was deeply transformed by the spread of glassblowing (Larson 2019).

By the second half of the first century CE, glass blowing supplanted the older techniques of slumping and core-forming. The rapidity of execution and the possibility of saving glass in the production of thin-walled vessels were certainly decisive factors behind the success of the new technique. The propagation of glass-blowing led to a higher demand for glass and a lower price for vessels. The effects of this change are clearly reflected in the diffusion of functional containers conceived for everyday use (Stern 1999).

The peak of glass consumption recorded throughout the Roman Empire in the first half of the first century CE appears to be confirmed by an increasing amount of glass in urban waste. Little attention has been paid to the chemical composition of first-century glass and most of the literature available is on glass from sites located on the Adriatic coast (Gliozzo 2017; Silvestri et al. 2018; Gliozzo et al. 2023). At present it is extremely difficult to identify a clear trend in glass recycling. The collection of broken glass in Rome is cited in two well-known passages of the Latin poets Statius and Martial, who wrote during the last quarter of the first century CE (Whitehouse 1999), but the real impact of glass recycling during the early Roman Empire has never been assessed systematically. When Robert Brill (2012) analysed a selection of glass vessels from Pompeii, he identified some recycled compositions. A recent study on glass, ceramics and metals excavated at the Sarno Baths and in other Roman landfills, compared to the amount of glass, ceramics and metals in primary depositions concluded that glass was recycled systematically in Pompeii during the first century CE (Furlan and Andreatta 2023). Our study is the first integrated archaeological and chemical investigation aimed at reconstructing the multi-layered dimensions of the glass economy in Pompeii in the first century CE. We explore the provenance of the glass, the intensity of recycling, and the glass-working techniques used for the vessels. The identification of one moil in the dump of the Sarno Baths is noteworthy. This find is the first proper indicator of glassblowing ever documented in Pompeii and strongly supports the hypothesis that a glass workshop existed in town. This identification opens up new perspectives for the study of the dynamics of glass working and recycling in the Vesuvian centre. We discuss the different reasons which justified the presence of a glass workshop in Pompeii. In particular, we look at the connection between the demand of glass and the perfume industry which flourished in Pompeii and in the Vesuvian region during the first century CE.

Archaeological context

In 2016, the project MACH – Pompeii, conducted by the University of Padua (Artioli et al. 2019), offered a thorough re-examination of the Sarno Baths located on the southern edge of the Vesuvian site (Regio VIII, insula 2). Positioned

between the Sanctuary of Venus to the west and the so-called Triangular Forum to the east, the Sarno Baths a monumental 6-storey structure leaning against the southern slopes of the plateau of the urban area (Fig. 1a and c). The architectural history of the building (Bernardi et al. 2019; Bernardi and Busana 2019) is still uncertain, and includes the incorporation of various structures and blocks in different periods. A major architectural phase seems to have taken place in the Augustan period, while the building underwent extensive refurbishments after the earthquake of 62/63 CE and was probably only partially inhabited in 79 CE. The function of the complex, which comprises almost a hundred rooms, is still a matter of debate, and a mixed use that includes both private and public activities (domestic, recreative and/or institutional) may be a valid option. The new investigations carried out in 2016 included the geophysical survey of the area immediately outside the building (Deiana 2019), and the excavation of a 21 × 2.5 m trench perpendicular to the façade, to shed light on the topographical, environmental and chronological context of the construction (Furlan et al. 2019) (Fig. 1b-d). The excavation was eventually complemented in 2017 by a series of mechanical cores drilled

further south, which documented the presence of a marshy area extending up to the Sarno river (Nicosia et al. 2019; Vignola et al. 2022).

The excavation of the trench exposed a complex stratification, the sequence of which can be outlined, in ascending chronological order, as follows (Fig. 2a-b):

- Phase 1. Geological substratum (limit of the plateau).
- Phase 2. Probable colluvial deposit (inclined southwards).
- Phase 3. Dump deposits (inclined southwards).
- Phase 4. Dump deposits (inclined southwards).
- Phase 5. 79 CE Mount Vesuvius eruption deposits (inclined southwards).
- Phase 6. Evidence of post eruption activities.
- Phase 7. Horizontal truncation of the lower sequence and twentieth century backfill.

The presence of abundant refuse, the absence of any indicators of natural deposition (other than gravity and the infiltration of sediments) and the lack of any constructive function indicate that the core of the deposit, which is articulated in two phases, is the result of dumping activities

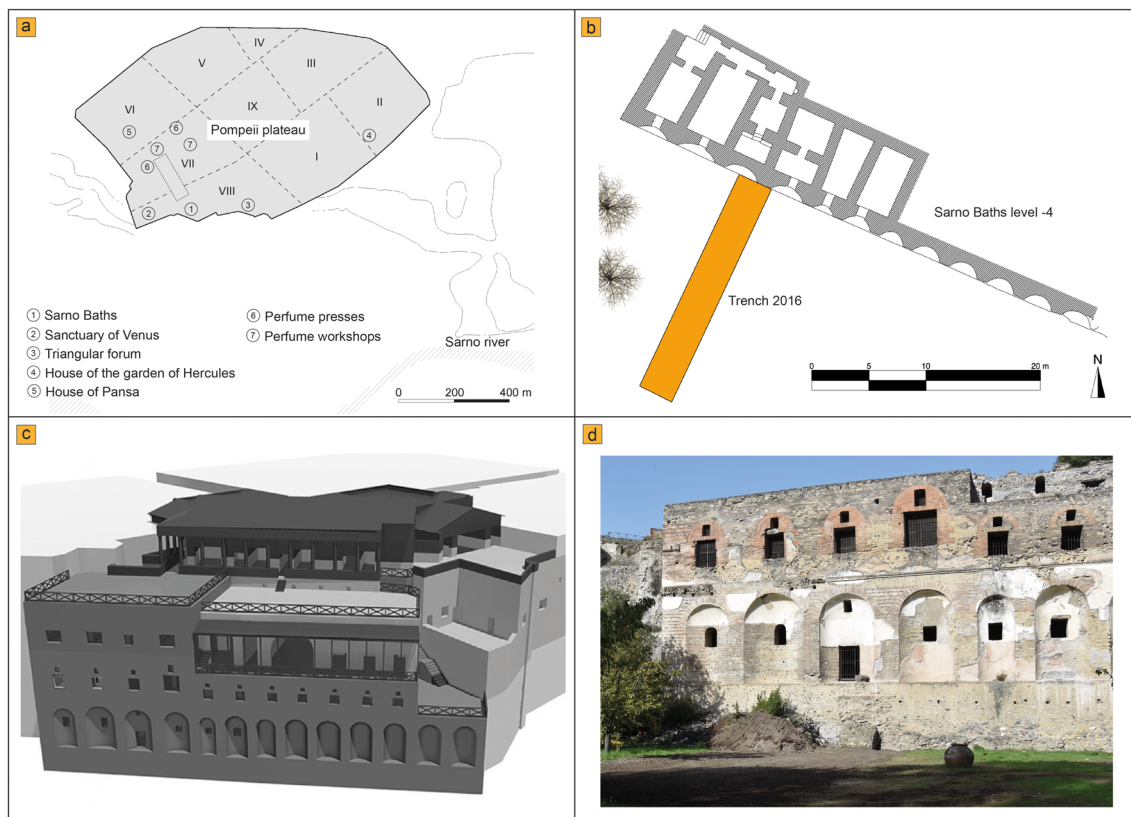


Fig. 1 a Location of the Sarno Baths complex in Pompeii; b plan of the building and location of the trench excavated in 2016; c reconstruction of the complex as seen from the south; d view of the façade

of the Sarno Baths at the end of the excavation. Images from Bernardi et al. 2019, elaborated by Guido Furlan

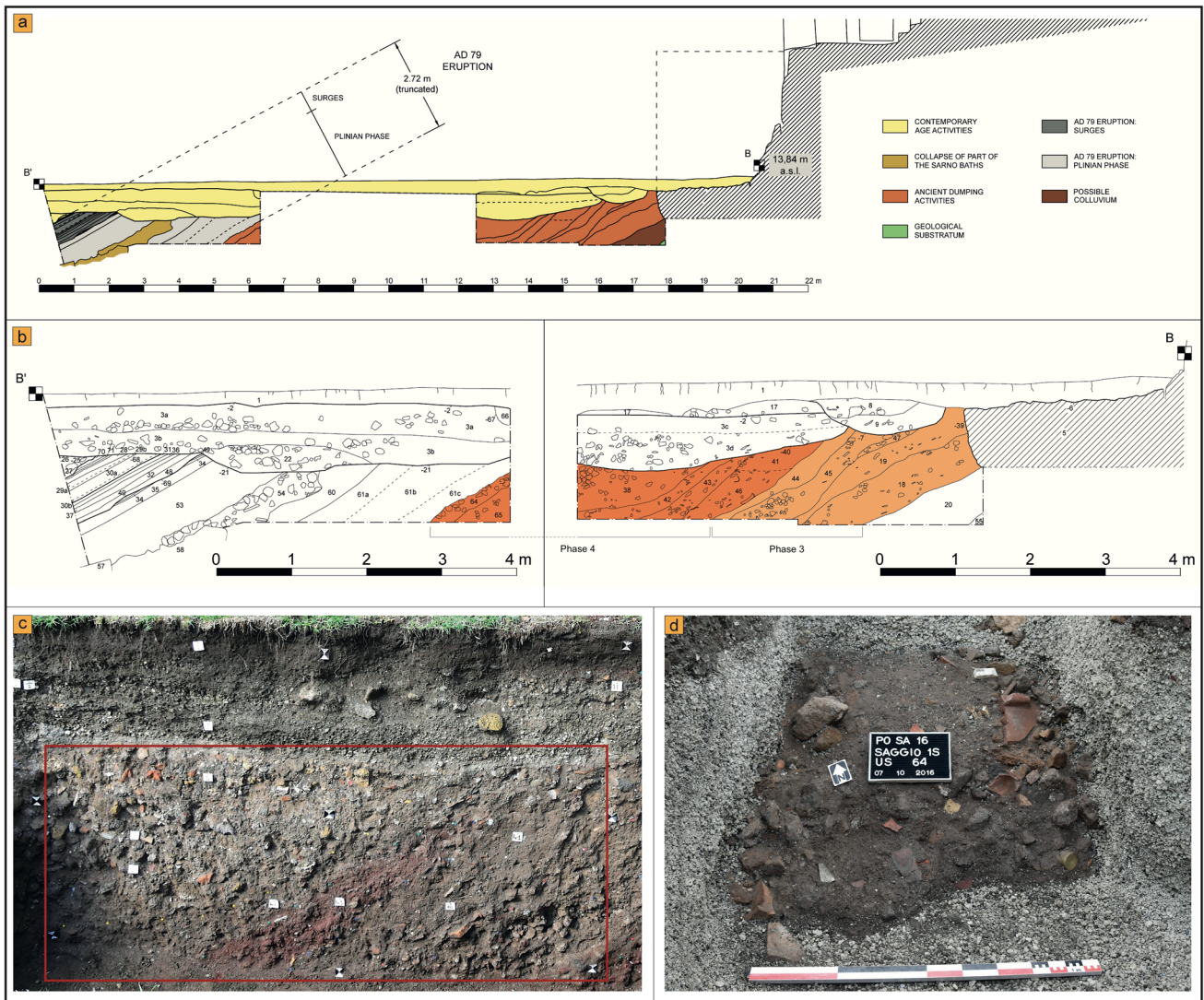


Fig. 2 **a** Profile of the western side of the trench excavated in 2016; **b** detail of the profile with the contexts discussed in text marked in orange; **c** view of the cross section of the northernmost contexts discussed in the paper (38, 42, 43, 41 = 46); **d** view of context 64, result-

ing from the most recent dumping activities documented before the Mount Vesuvius eruption occurred in 79 CE (white pumices in the picture). Images from Furlan, Bonetto, Nicosia 2019, elaborated by Guido Furlan

(phases 3, 4, Fig. 2b). Landfills were characteristic of liminal areas (Raventós et al. 2000; Ballet et al. 2003; Furlan 2017) and fit perfectly into the investigated suburban environment, which is bordered by the northern plateau and the southern marshland. Although the global extension of the dump is unknown, it is likely to have run for some meters along the city boundary, similarly to an urban landfill that was investigated in the northern outskirts of the city (Romanazzi and Volontè 1986). Glass was absent from the deposits of phase 3 (context numbers, in depositional order, 18, 19, 47, 45, 44), which produced abundant black-glazed ceramics and can be provisionally dated between the second and the first centuries BCE. The material explored in this paper belongs to the second dumping phase, here named phase 4 (context

numbers, in depositional order, 41 = 46, 43, 42, 38, 65, 64. Figure 2b and c). The preliminary study of the ceramics points to a *terminus post quem* around the mid-first century CE and indicates a general chronological uniformity (Andreatta 2018). This supports the interpretation of the deposit as the product of dumping activities rather than backfilling. Although the amount of residuals is low, the majority of the assemblage is, on average, slightly older than the moment of deposition. The discrepancy does not surprise (Hill 1982; Furlan 2019, pp.93–8 and 118–54) and may be related to the inaccurate dating of many ceramic types and to a production-deposition delay, due to the use-life of artefacts and the possible temporary disposal of what was to be permanently discarded. This means that the assemblage

also informs us about a period slightly before the 50 s CE, a fact confirmed by the study of the glass finds. Completion of the study of the whole assemblage may lead to further chronological refinements, particularly in relation to the role of the post 62/63 CE (earthquake) activities in the formation of the deposit. In fact, the study of the glass finds suggests that deposition is likely to have begun after this episode. Finally, dumping activities were probably still taking place right before the 79 CE eruption of Mount Vesuvius, when the most recent context, still rich in empty recesses, was covered by white pumices (Fig. 2d).

In terms of the quantity of finds ($n = 2027$), the assemblage recovered in the second phase of the dump, includes 60% of ceramics (5% lamps, 14% amphorae, 17% cooking ware, 24% fine and storage ware), 27% of building materials (in particular painted plaster), 9% of organic residue, 2% of glass, and 2% of metals. This provides the picture of a deposit made of mixed refuse, apparently reflecting domestic environments. On the other hand, the presence of building material is coherent with a phase of reconstruction which may be related to the years following the earthquake of 62/63 CE. The nature of this archaeological context makes it an excellent source of information to explore the local economy at sub-site level, in a fairly narrow time-frame. In other words, it reflects ancient consumption trends more clearly compared to secondary deposits excavated within the city boundary. Concerning glass and metals, however, the picture is more complex: largely remelted before reaching the dumping sites, they represent, in absolute terms, a rarity (4% in total). The amount of glass deposited in the dumps of the Sarno Baths is sensibly lower than in the primary contexts obliterated by the Vesuvius eruption. This depositional pattern informs us of the effectiveness of the recycling system of the town (Furlan and Andreatta 2023).

Materials and methods

We discuss the chemical composition and the typology of 46 glass finds excavated from the dumps of the second phase, which are the totality of glasses retrieved during the stratigraphic investigations (with the exception of one game counter, not considered in this study because the temporary export of the find was not authorised) (Tab. 1SI, Figs. 3–4). The assemblage includes monochrome blown and slumped vessels ($n = 41$), windowpanes ($n = 3$), one decorative inlay and one moil. Apart from one opaque green vessel and the inlay, which is turquoise, all the samples are transparent or translucent. Most of the fragments are colourless with a green–blue tinge, some fragments are visibly decoloured and the assemblage also includes vivid shades of translucent blue, emerald green, amber, and purple. The glass vessel fragments were classified according to the typology of

Isings (Isings 1956) and for the *unguentaria* according to De Tommaso (De Tommaso 1990). Millimetric chips of glass were freshly fractured from the clean fragments and were analysed without any further preparation by laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) at IRAMAT-CEB in Orléans (France), following the standard analytical protocol as published by Gratuze (Gratuze 2013, 2016; Schibille et al. 2024). The instrumental set-up consists of a Resonetics M50E excimer 193 nm laser and a Thermo Fischer Scientific ELEMENT XR mass spectrometer. A stationary laser beam with a diameter of 100 μm (occasionally reduced in case of saturation caused by e.g. Mn), an energy of 5 mJ and a pulse frequency of 10 Hz were used for the analyses. Analysis was preceded by a pre-ablation of 15 min to remove any possible surface alteration and eliminate the transient part of the signal. 58 different isotopes from lithium to uranium, chosen so as to minimise potential interference, were measured for approximately 27 s. The sampled material is then transported by an argon/helium flow (1 l/min Ar + 0.65 l/min He) to the plasma torch, where the material is dissociated, atomized and ionized at high temperature (8000 °C). The separated ions are analysed using either a secondary electron multiplier (SEM) or the Faraday detector for ^{23}Na , ^{27}Al and ^{39}K (Gratuze 2016). ^{28}Si serves as an internal standard, while background measurements taken at regular intervals are subtracted from each analysis. The response coefficients for each element is calculated based on five different reference glasses (NIST610, Corning B, C, D and APL1) and quantitative data are obtained following the method described by Bernard Gratuze (Gratuze 2016). The data of the reference glasses are given in Supplementary Table S2, reflecting the accuracy and precision of the measurements.

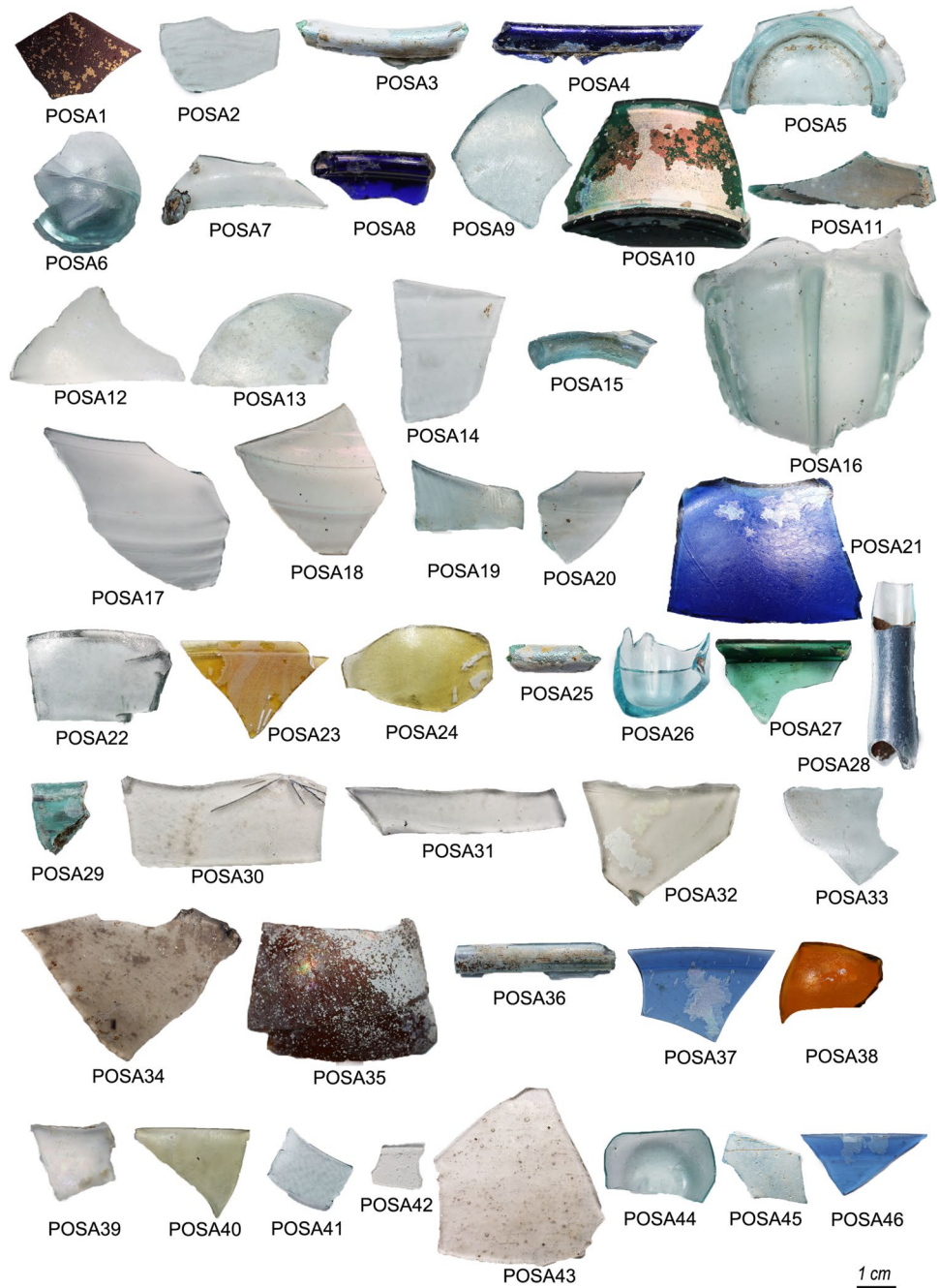
Results

Forming technique and typology

Vessels

The forming technique is the first criterion used in this study to divide the fragments of vessels in macro groups, to discuss their chronology and to reflect on their possible value. The 41 vessel fragments include 4 slumped and 37 blown artefacts (Figs. 3–4). These figures represent faithfully the trends in glass-working documented between the second decade of the first century CE and the 50s, when blowing had become the most popular technique, but slumped vessels were still relatively common (Larson 2019). Slumping is based on the principle of pressing a disc of soft glass in an open mould. This technique is very convenient to fashion open forms, but can be adapted to closed forms, combining moulding and

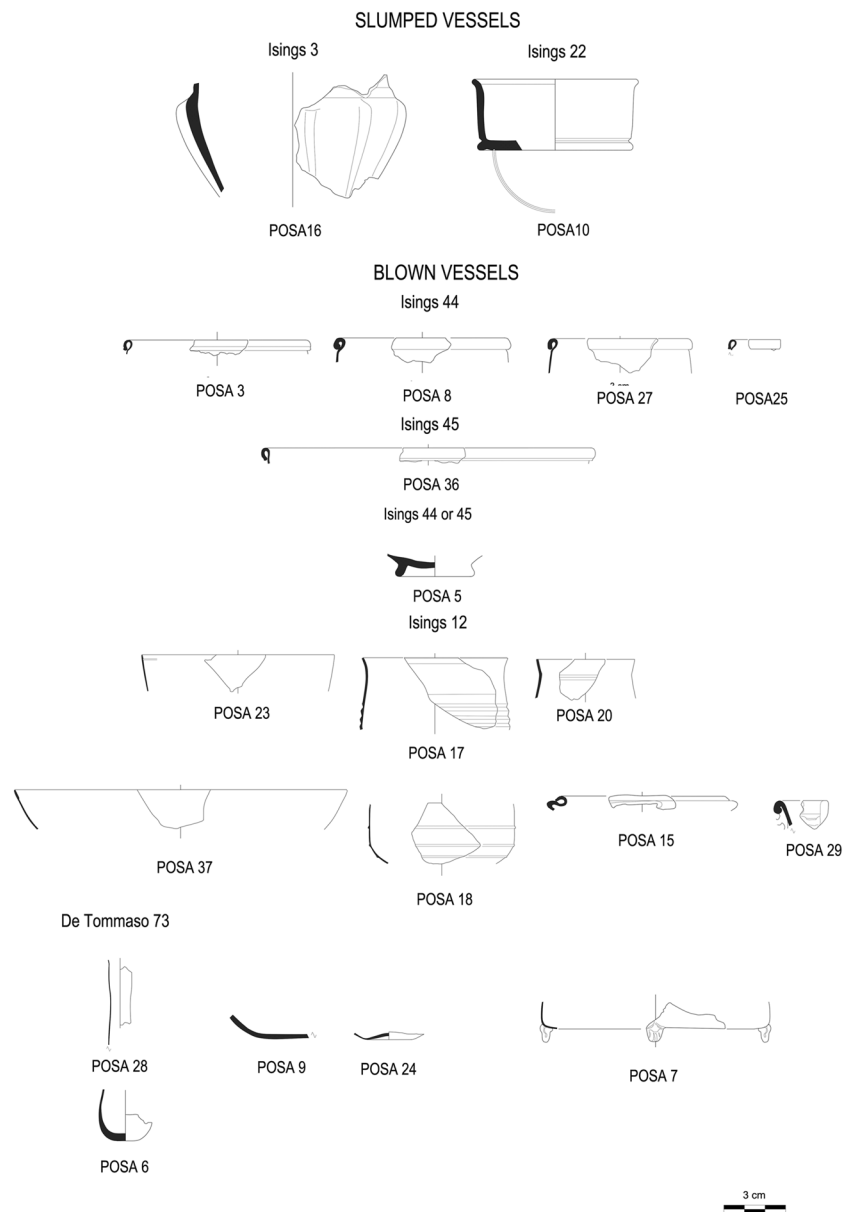
Fig. 3 The glass fragments from the dump of the Sarno Baths. All the fragments are vessels, with the exception of POSA26 (moil), POSA30-32 (windows), POSA 45 (inlay). Photos: Cristina Boschetti, courtesy of Archaeological Park of Pompeii, Italian Ministry of Culture



the manipulation of the hot glass with the help of jacks and tongs. In some cases, such as the bowls of Isings 3, the ribs were obtained by pinching the outer surface of the vessel with iron rods. After cooling, the surface of slumped vessels was always finished by polishing on the potter's wheel and eventually by cutting thin decorative lines at the lathe (Fig. 1SI, photo CB, courtesy Italian Ministry of Culture, Archaeological Park of Pompeii). It is generally believed that only one face of slumped vessels –the face which did not enter in contact with the mould– needed to be smoothed by cold-working, to eliminate the asperities due to the moulding

process (Petrianni 2003). One fragment from the dump is polished on both sides (POSA10) and makes an exception to this rule (Figs. 2 and 3SI, photos CB, courtesy Italian Ministry of Culture, Archaeological Park of Pompeii). This apparently unnecessary technical procedure may have been an aesthetic choice, because polishing confers a satin finish to the surface. Only two slumped fragments can be clearly associated with a type: the colourless bluish-green ribbed bowl of Isings 3 (POSA16) and the emerald-green dish of Isings 22 (POSA10). The bowls of Isings 3 are documented stratigraphically in Pompeii as early as the end of the first

Fig. 4 Drawings of the different slumped and blown vessels excavated, with indication of the sample and, when possible, of the corresponding type (drawings Silvia Tinazzo, Dept. of Cultural Heritage, University of Padova)



century BCE (Scatozza Höricht 2012, p.85), but the variant in colourless bluish-green glass, like the one identified at the Sarno baths, is very rare before the third/fourth decade of the first century and will become the most popular colour in the post-62/63 CE contexts (Cool 2016, p.119). The straight-sided slumped dish of Isings 22 is an uncommon form and is documented almost exclusively in emerald green glass (Jackson and Cottam 2015; Cottam and Jackson 2018). In Pompeii similar dishes were excavated in contexts of the first half of the first century CE as well as in post-62 contexts (Scatozza Höricht 2012, p.208; Cool 2016, p.115).

All the blown vessels are free blown. On eleven of these fragments the polishing lines are well visible. This process is in theory redundant in the manufacture of blown vessels but, as already noted in relation to the slumped vessels, the

most straightforward explanation is that a non-glossy surface was appreciated. Before the diffusion of glass blowing, cold working was systematically integrated in the manufacturing process of glass vessels and was evidently mastered by the artisans operating in the glass workshops. The popularity of cold working of blown vessels shows that throughout the first century, even after the spread of glass blowing, this skill was not lost and continued to be practiced. The majority of the diagnostic blown fragments are rims. Seven tubular rims formed by being bent out and down belong to deep cups of Isings 44 (POSA 3, 4, 8, 10, 25, 27) and, in one case, to the shallow form of Isings 45 (POSA 36). These two types are amongst the earliest blown forms documented in Italy, at the end of the first century BCE (Grose 1977). As noted by Cool in the discussion of glass finds from Insula 5 of Regio

VI, colourless bluish-green examples of Isings 44 and 45 are rare in Pompeii before the 62/63 CE earthquake and have a peak in the eruption layers, when they represent half of the documented specimens (Cool 2016, p.142). In our case, four fragments exhibit strong colours (translucent blue and emerald green) and three are colourless with a blue-green tinge. These characteristics ascribe them to the years close to the 62/63 earthquake.

One amber-yellow and three colourless crack-off rims can be identified with variants of beakers Isings 12 (Figs. 3 and 4). The amber-yellow fragment (POSA23) is hemispherical and measures 10,7 cm in diameter. The vessel is polished on the inside and on the outside, with one single groove-cut line on the interior, under the rim. The other three fragments belong to ovoid beakers, with lathe-cut lines and wheel polishing on the exterior (POSA17, 20, 40). The two measurable fragments have a diameter of 5,4 and 8 cm. The hemispherical and ovoid variant of the Isings 12 beaker do not appear in Pompeii before the Tiberian period and tend to go out of fashion at the end of the reign of Nero (Cool 2016, p.127). Two fragments of colourless walls (POSA 14, 41) decorated on the exterior by wheel-cut lines can be tentatively associated with the same type. Two cracked-off and ground and one hot-polished rim belong to forms which are not included in the Isings classification. These fragments find rare parallels in the Vesuvian region and represent perhaps imports from the eastern Mediterranean. The two cracked-off rims are translucent blue (POSA37, 46). They are not joinable, but are potentially part of the same vessel, a thin-walled shallow bowl with a diameter of 18, 4 cm, rotary-polished on the inside and on the outside. The inside was carved to create a small step under the rim (Fig. 4SI, photo CB, courtesy Italian Ministry of Culture, Archaeological Park of Pompeii). The only published parallel in Pompeii is one fragment excavated from a Tiberian context in Regio VI, 5 (Bardelli Mondini 1984, pp.263, 269 Tav. 146). Similar bowls, presumably excavated in Rome, are documented in the Gorga collection and were identified by Petrianni as slumped vessels, classified under the type Gorga 9 (Petrianni 2003). This identification of the forming technique was based on the presence of polishing lines, but as can be clearly seen in Pompeii, surface polishing was not exclusive of slumping. The reduced thickness of these vessels is better compatible with blowing rather than slumping.

The same observation can be made for one wall (POSA18) with raised horizontal bands on the body and polishing lines on the exterior, which Petrianni attributes to a slumped variant of the beaker Isings 29 (Petrianni 2003). Blown vessels with this kind of decoration have parallels in Italy and in Pompeii during the second half of the first century CE (Bardelli Mondini 1984, p.265). One minute fragment of decoloured fire-rounded rim (POSA42) can be probably associated to a similar fragment of a cup excavated

in Regio VI, 5 and interpreted as an import from the eastern Mediterranean, possibly Egypt or Cyprus (Bardelli Mondini 1984, pp.263, 269. Tav. 146). The group of rims is completed by two colourless blue-green thick folded rims, which do not retain enough walls to propose a safe identification. They can be tentatively identified as a jar (POSA29) of Isings 62 and an ointment jar of Isings 68 (POSA15), two forms common in Pompeii after 50 CE.

Only five blown fragments are bases and none of them retains the mark left by the pontil, the iron rod used to hold the vessel during the different phases of construction of the vessel. There is disagreement on when and where the pontil started to be used by glass workshops and some scholars believe that it was introduced only around the third quarter of the first century (Whitehouse 2015). The external surface of the base of the unguentarium POSA44 and the beaker POSA33 hold the mark of tongs, which fulfilled the function of the pontil (Fig. 5SI, photo CB, courtesy Italian Ministry of Culture, Archaeological Park of Pompeii). The colourless bluish-green ring base POSA5 can belong to a cup of Isings 44 or to a dish of Isings 45. One of the bases (POSA6) belongs to a tubular unguentarium of De Tommaso 73, the most popular perfume and medicine container documented in Pompeii, during the first century CE. The base with shallow conical kick (POSA24) and the flat base POSA9 cannot be attributed precisely to a type, but was surely part of one unguentarium. The group of bases is completed by a fragment for which, at present, there is no parallel (POSA07). It is footless and flat, with straight walls and one small indentation applied to the base. The diameter is 10,7 cm. This container can be tentatively identified with a pyxis, or a beaker. The corpus of vessels is completed by a tubular fragment with a constriction at the centre (POSA28). It can be associated to the already cited unguentarium of De Tommaso 73 or to a funnel of Isings 74, a form documented from the mid to the end of the first century CE (Cool 2016, pp.153–4).

Windowpanes and inlays

The presence of three fragments of windowpanes (POSA30, 31, 32) in the dump is noteworthy (Fig. 3). The Latin author Seneca, who died in 64 CE, mentioned glass windows as a recent invention of his times (Sen., *Ad Lucilium Epistulae Morales*, XC, 25). The accuracy of this source is confirmed by the archaeological record of the Vesuvian sites, where glass windows are documented sporadically and, in most cases, to close the openings of public baths (Dall'Acqua 2004; Wiesenberg 2022). These early window panes were formed by pouring and manipulating the hot glass on the marver, to obtain a rectangular slab (Allen 2002). Before the installation, the slab was cut to the desired shape and size. One of the fragments from the Sarno landfill (POSA43) shows clearly the lines traced as guidelines to snap the glass

(Fig. 5SI, photo CB, courtesy Italian Ministry of Culture, Archaeological Park of Pompeii). These marks were probably obtained with a wheel blade. Finally, one flat fragment of opaque turquoise glass, without any trace of surface polishing, is an inlay (POSA45). Inlays belong to the Egyptian tradition and were used to decorate portable wooden objects, like caskets and furniture (Bianchi 1983). In the Roman Empire inlays started to be employed in architecture, but only from the end of the third century (Gasparini 2022). The fragment from the Sarno landfill was most likely applied on an object, like a piece of furniture or a casket.

Chemical composition

The full chemical composition of the glasses analysed in this study is presented in the supplementary materials (Tab. 1SI). The majority of the samples ($n=40$) follow the dominant technological trend of the Roman period and are natron-type glasses, with low magnesium and potassium oxide concentrations ($< 1.5\%$) (Sayre and Smith 1961; Shortland et al. 2006). Five emerald-green vessel fragments have higher magnesium, potassium and phosphorus levels that indicate the presence of a plant ash component. The exceedingly low impurity levels of sample POSA39, especially in relation to Al_2O_3 , MgO , P_2O_5 , Cl , K_2O , B , Sr and REEs, indicate the use of synthetic raw materials and identify this fragment as modern intrusion and is not further discussed.

Based on the ratio of $\text{Al}_2\text{O}_3/\text{SiO}_2$ versus $\text{TiO}_2/\text{Al}_2\text{O}_3$ and Y/Zr versus Ce/Zr , different base glass groups can be distinguished (Fig. 5a and b). Most glass samples ($n=36$, Roman Mn) from the Sarno Baths have moderate alumina contents ($\sim 2.6\text{ wt}\%$), relatively high calcium oxide ($\sim 8.2\text{ wt}\%$) and overall low transition metals and rare earth element (REE) concentrations. A sub-set of samples ($n=6$) in the Roman Mn main group differs in having slightly higher heavy element concentrations (group “high Zr” Tab. 1SI). Three samples have notably lower alumina ($\sim 1.75\text{ wt}\%$) and calcium oxide ($\sim 5.1\text{ wt}\%$) and somewhat higher transition metal signatures (POSA18, 42, 45). The five emerald green samples with a plant ash component have even higher impurities

related to the glassmaking sand. Taken together, the use of three very different silica sources and by extension different primary productions can therefore be assumed. More specifically, the main group is consistent with glass made from a Syrio-Palestinian silica source on the Levantine coast, while the three outliers and the emerald-green glasses are more likely to be of predominantly Egyptian origin on account of their higher heavy element contents.

The difference in origin is also reflected in the presence or absence of manganese and/or antimony. In Roman times, natron glass was commonly decolourised during the primary glass production stage (Jackson 2005; Gratuze 2018; Paynter and Jackson 2019). The primary workshops that were active in Egypt during the imperial period used antimony as decolouring agent and produced a glass with antimony above the levels naturally contained in sands ($> 30\text{ ppm}$), while glassmakers active in Syria-Palestine privileged manganese and produced glasses with manganese above the natural levels contained in the silica source ($> 250\text{ ppm}$) (Freestone 2015; Gliozzo 2017; Barfod et al. 2020; Schibille 2022). The simultaneous presence of both elements ($\text{Sb} > 30\text{ ppm}$, $\text{Mn} > 250\text{ ppm}$) suggests mixing and recycling of different base glasses (Freestone 2015; Gratuze 2018; Barfod et al. 2020; Schibille 2022). The majority of the colourless and decoloured samples from the Sarno Baths in Pompeii have high Mn ($> 250\text{ ppm}$) and low Sb ($< 30\text{ ppm}$) levels, which confirms that these glasses originated from Syro-Palestinian primary workshops (Fig. 5c, Tab. 1SI). They include blue-green and decoloured vessels – all blown, with the exception of three slumped specimens – and the three decoloured windowpanes. Three vessel fragments (Roman colourless) have very low manganese concentrations ($< 200\text{ ppm}$) that can be considered an impurity from the silica source. They are part of the naturally coloured Syro-Palestinian type that has been documented occasionally during the first and second centuries CE (Jackson and Paynter 2016).

Antimony occurs either as opacifier or in combination with glass that also contains manganese. The highest concentrations of antimony are to be found among the minor compositional groups. In sample POSA45, for example,

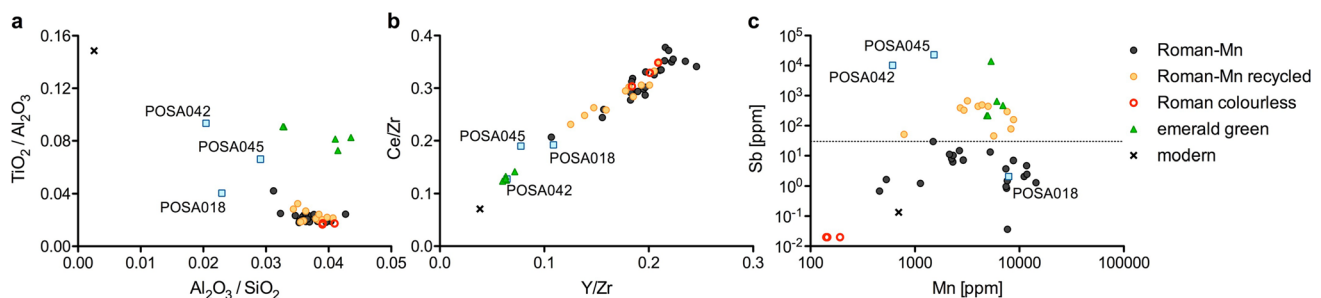


Fig. 5 **a** $\text{TiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{SiO}_2$ and **b** Ce/Zr and Y/Zr ratios are indicative of the silica source used to make the glasses. **c** The simultaneous presence of both Mn and Sb above natural levels is index of mixing and recycling. Graphs: Nadine Schibille

calcium antimonate most likely acts as an opacifier (Shortland 2002; Lahlil et al. 2010; Freestone and Stapleton 2015; Boschetti et al. 2020). The colour of this turquoise inlay is due to a combination of cobalt and copper, the latter probably introduced as bronze scale, as shown by the elevated tin concentration. The base glass features, such as low alumina, low lime and high soda contents correspond to Egyptian Sb-decoloured glass produced between the first century BCE and the first half of the first century CE (Paynter and Jackson 2019). Sample POSA42 can likewise be regarded as Roman Sb-decoloured glass from Egypt, although a small amount of manganese is present, possibly a pollution caused by glass working, in a workshop where Roman-Mn glass was also available. Moreover, all emerald green fragments with a plant ash signature contain significant concentrations of antimony, indicating recycling. They appear to have been produced by mixing emerald green plant-ash glass with colourless Egyptian-Sb natron glass or, in the case of the opaque sample (POSA11), to a white natron glass, opacified with calcium antimonate. Apart from the elements associated with plant ash, the emerald green glasses are distinctive for the high levels of transition metals such as titanium, zirconium and hafnium that all point to the use of an Egyptian silica source. In this respect they correspond to the emerald green glass typical of the first century CE (Jackson and Cottam 2015; Cottam and Jackson 2018).

Ten samples belonging to the Syro-Palestinian Roman-Mn base glass group that have not been intentionally coloured, including eight blown vessels, the ribbed bowl of Isings 3 and the moil, have elevated antimony levels (> 30 ppm) as well as other colouring elements such as copper, cobalt, or lead (> 100 ppm). These features indicate that coloured cullet was introduced through mixing and recycling at some point in the life cycle of these glasses. The chemical composition of the coloured glass recovered from the Sarno Baths is in line with the literature on first-century CE glass. The amber-yellow samples do not deviate from the composition of the Roman colourless samples. The colour is in fact most likely the result of an electron exchange between sulphur S^{2-} and iron Fe^{3+} , hence dependent on a reducing atmosphere during glass working (Paynter and Jackson 2018). Three of the five blue samples and the purple fragment are Roman-Mn glass coloured by a combination of copper and cobalt to obtain blue, and by manganese for purple. In short, the coloured glasses are mainly of the Roman Mn type. Two blue samples are an exception. The blue rim POSA18 is more closely related to an Egyptian base glass due to the higher soda concentrations and high transition metals coupled with lower alumina. In this, the sample shares close similarities with Foy 3.2, a base glass produced in Egypt during the fifth century CE, but it cannot be clearly associated to any well-documented base glass composition of the first century CE (Balvanović and Šmit

2022). Finally, the transparent blue fragment of a slumped vessel (POSA21) has higher antimony contents than any of the other blue specimens, probably as a result of mixing and recycling some Sb-opacified blue glass with a transparent Roman-Mn blue glass.

Discussion

Chronological considerations

The technological and typological analysis of the vessels narrows down the chronology of the glasses from the dump. The identified forms find parallels in glass from Pompeian contexts of the first half of the first century CE. Most of these types continued to be used until the Mount Vesuvius eruption, but any of the new types, which were very popular during the very last years of the city, are completely missing from the landfill. The most significant data is the lack of square bottles of Isings 50, which were used for the wholesale of essential oils as well as kitchen containers found extensively in the 79 contexts (Scatozza Höricht 2012, pp.30, 32–5). These bottles are documented as early as the 40 s, but become prominent only during the very last years of Pompeii (Cool 2016, p.153), as can be seen from the survey conducted on glasses from the entire Regio I (Scatozza Höricht 2012, p.38). The same typo-chronological pattern was observed in the preliminary studies of fine ceramics retrieved from the dump (Andreata 2018). This result indicates that the earthquake of 62/63 CE can be considered a possible starting date for the second phase of the dump, when the city entered a period of reconstruction. In 79 CE many private and public buildings were still condemned and building sites were active in town almost everywhere (Andreau 1973).

Base glass supply in Pompeii

The dominant base-glass composition documented in our assemblage (73%) is Roman-Mn glass made in Syria-Palestine. Stocks of fresh Roman-Mn glass continued to supply Pompeii until the time of the eruption, as documented by the blocks of raw glass excavated in the area of the *Insula Occidentalis* (House of Marcus Fabius Rufus) (Brill 2012). The clean Roman-Mn chemical composition observed in the blue, purple and amber samples shows that colouring was controlled to avoid the accidental introduction of colourants and opacifiers. Amber and, maybe, purple were possibly obtained either during glassmaking or in secondary workshops which operated using glass of a Syro-Palestinian composition (Roman Mn or Roman naturally coloured), maybe close to the primary glassmaking

installations. This hypothesis is coherent with the finding of blocks of amber-yellow glass adhering to the walls of a tank furnace excavated in Beirut, dated between 100 BCE and 50 CE (Kouwatli et al. 2008). During the first century CE, the primary workshops supplied the secondary workshops with unworked coloured glass, alongside blocks of colourless glass, as documented by the finds of coloured raw glass in the glass-blowing workshops of Avenches (Switzerland) and Lyon (France), both active in the mid-first century CE (Foy 2000; Robin 2016; Cottam and Jackson 2018). The absence of indicators of glass colouring, like colour tests, in Avenches and Lyon supports the hypothesis that the workshop was supplied with coloured glass (Cottam and Jackson 2018). The Mediterranean-wide trade of coloured glass is known since the Late Bronze Age (Pulak 1998; Jackson and Nicholson 2010). Lumps of transparent cobalt-blue and opaque yellow glass formed part of the cargoes of the late fourth- to early third-century BCE shipwreck of Su Pallosu, which had sunk off the western coast of Sardinia (Salvi 2006). A century later, cobalt-blue glass was transported by the “Sanguinaire A” ship that had sunk off the west coast of Corsica (Cibecchini et al. 2012). Unfortunately, there is a gap in the evidence for shipwrecks with cargo made of unworked coloured or colourless glass between the second century BCE and the second half of the first century CE (Nenna 1998). In Pompeii, an early availability of unworked decoloured and coloured glass is documented by the floors of the House of the Faun (Regio VI 12, 2). In this lavish building large quantities of blocks of decoloured glass and fragments of opaque red glass cakes were used to pave the corridor of the peristyle and of two reception rooms, dated between the end of the second and the beginning of the first century BCE (Boschetti 2011). The chemical composition and isotopic signature of these glasses assign them to the Syro-Palestinian region (Boschetti et al. 2016, 2017). The results obtained on the glass finds from the Sarno Baths show that the flux of Syro-Palestinian coloured glass probably continued through the first century CE.

The paucity of published Egyptian base glasses of the first century CE limits our understanding of the role of Egypt in the international glass market during the early imperial period. The Roman Sb-glass from the Sarno Baths is the second glass of this type ever documented in Pompeii (Brill 2012). This helps us define the earliest date for the circulation of this composition, which is presently set between the end of the first century and the beginning of the second century (Robin 2016, p.148). Taking into consideration the unusual typological characteristics of the Roman-Sb vessel identified in the dump, it is likely that this vessel was imported from Egypt as a finished object. The same conclusion can be reached for the turquoise inlay, given the peculiarity of these objects and their strong connection to the Egyptian tradition

(Bianchi 1983). The other natron sample of Egyptian origin (POSA18), which at present cannot be clearly affiliated to any well-defined compositional group, evokes the scenario of a non-fully centralised Egyptian glass industry, which still needs to be explored in depth. The identification of emerald-green Egyptian plant-ash compositions is consistent with this model. The use of plant-ash for emerald-green glass is explained as functional to achieve the desired colour as much as plant ash can contribute to a reducing atmosphere, which is most likely needed to obtain emerald green (Jackson and Cottam 2015; Cottam and Jackson 2018). Interestingly, plant-ash compositions are occasionally documented during the first century in coloured glasses for which the selection of the plant-ash component has no clear explanation. This is the case of one transparent blue vessel from Pompeii (Brill 2012) and of the transparent blue glass-blowing debris from the workshop of Avenches in Switzerland (Cottam and Jackson 2018). Plant-ash compositions are documented in Egypt during the fourth-third century BCE, in the glass workshop active in the temple of Tebtynis (Nenna and Gratuze 2009; Bettineschi and Angelini 2023) and during the first–second century CE in Bubastis (Rosenow and Rehren 2014). The diffusion of plant-ash compositions is also documented by the chemical composition of mosaic vessels presumably made in Egypt and excavated in western-Europe and in Somalia (Nenna and Gratuze 2009). The existence of a plant-ash tradition in Egypt, where natron was easily available, might look surprising. A possible explanation can be sought in the high-degree of conservatism of the Egyptian workshops, which perpetrated older productive practices. This pattern can be observed, for instance, in the first-century BCE glass cakes from Denderah, which look identical to the Late Bronze Age cakes from Egypt (Boschetti 2018).

Glass blowing and recycling in Pompeii

The moil found in the dump is the first indicator of glass-blowing ever documented in first-century Italy and suggests that glass-blowing was practiced in Pompeii. The chemical composition of the moil corresponds to recycled Roman-Mn glass, just like 32% of the natron glasses analysed in this study (Fig. 5a-c, Tab. 1SI). The results of the glass from the Sarno Baths give rise to some thoughts on glass recycling in Pompeii. The total lack of glass in the first phase of the landfill is particularly telling. During the first century BCE glass vessels were available in Pompeii as in the rest of Italy, but they were used sparingly. Most of the documentation on glass of this period comes from funerary contexts, where vessels were deposited as grave goods (Gallo et al. 2013). Between the end of the second century BCE and 40/50 CE, fragments of monochrome and polychrome broken vessels were reused systematically in wall mosaics, documented

in several Italian sites, including Pompeii (Boschetti 2020, 2023). During the same period and until the end of the first century, the bead workshops active in the British islands employed fragments of coloured glass vessels, which were most likely sourced in the Mediterranean region (Jackson and Paynter 2022). The recent study published by Furlan and Andreatta on glass and metal recycling in the Roman Empire shows clearly that, in the first century CE, glass was carefully sorted from the urban waste of Pompeii (Furlan and Andreatta 2023). Taken together, the evidence suggests a model of careful glass collection and intense recycling which existed before the diffusion of glassblowing and continued throughout the first century CE. In the light of the preliminary chronology assigned to the dump of the second phase, this conclusion becomes even more interesting. Recycling in Pompeii did not stop during the emergency that began immediately after the 62/63 earthquake. The demand of glass in a town under major reconstruction was certainly high. Broken containers and windows were replaced. New mosaic decorations were created and, in some cases, damaged mosaics were repaired (Boschetti 2011). The increased demand due to this exceptional situation must be added to the already growing demand for glass, that followed the spread of glass blowing in the Roman Empire in the first half of the first century CE (Larson 2019).

Glass economy in Pompeii and the perfume industry

We are lacking information about the distribution and density of glass workshops in first-century Italy, but we have reason to believe that in Pompeii the demand of glass was significantly higher than in the average Roman town, not least due to the need of glass containers by the local perfume industry (Monteix and Brun 2009; Camodeca 2016). The quantitative data on glass vessels from 79 CE contexts in Pompeii show that perfume containers correspond to approximately 50% of the vessels recorded at the time of the eruption (Scatozza Hörich 2012, pp. 36–7). This percentage is exceptionally high compared to other contemporary urban contexts. At Cosa, for example, perfume and cosmetic containers do not total more than 10% (Grose et al. 2017). In his *Naturalis Historia*, Pliny the Elder reports that the production of perfume in Pompeii was higher than the production of olive oil in the other Italian regions (Plin. N. H. XVIII 111). This statement is undoubtedly hyperbolic, but the great importance of the perfume industry is confirmed by the archaeological record (Mattingly 1990; Borgard et al. 2003; Monteix and Brun 2009; Camodeca 2016). The Pompeian evidence of perfume-making is concentrated in the south-western sector of the city, not far from the dump of the Sarno Baths (Mattingly 1990; Monteix and Brun 2009). Two gardens of aromatic plants for perfumes are documented in Regio II (Insula 8, 6, house of the Garden of Hercules) and

in Regio VI (Insula 6, 1 house of Pansa) (Jashemski 1979). Two presses for the extraction of essential oils were identified in Regio VII (Insula 4, 24–25), in the insulae flanking the north-western side of the Forum, where the blocks of raw glass and the box full of new glass vessels were also found (Monteix and Brun 2009). Among the vessels were two square bottles bearing the mark of Publius Gessius Ampliatius, a freeman who was probably the owner of a perfume factory in the region (Taborelli 2017). Perfume workshops are documented nearby, along the via degli Augustali and via del Foro (Monteix and Brun 2009). We therefore assume that the glass workshops in Pompeii may have been located in the south-western sector of the city where the perfume workshops and the temple of Venus Fisica were situated. The sanctuary of Venus is in close proximity to the Sarno Baths landfill from where the glass was retrieved. The cult of Venus Fisica was linked to the city's economic activities (Battiloro and Mogetta 2021), most likely including also the perfume industry, which was an important business in Pompeii and was believed to be a gift of Venus herself (Butler 2010). This belief is illustrated in the famous Pompeian painting of the perfume workshop from the house of the Vettii, which depicts a statuette of Venus in a cabinet full of glass flasks (Mattingly 1990). Perfume workshops that were controlled by temples dedicated to Venus or equivalent goddesses such as Hator, can be found, for example, in Egypt, Palestine, Delos (Brun 2000) and Cyprus (Belgiorno 2017). A similar connection between the goddess and the perfume industry, and by extension glass workshops, may also have existed in Pompeii, where artisanal activities under the jurisdiction of temples are documented (Toniolo 2016).

Conclusions

The analysis of glass from the dump of the Sarno Baths provided the first conclusive evidence of the existence of glass working and recycling activities in Pompeii during the last couple of decades prior to the eruption of Mount Vesuvius in 79 CE. The main supplier of raw glass was Syria-Palestine; Egyptian glass is rare and reserved for specialised artefacts and/or colours. The glass assemblage as a whole also shows that recycling was already widespread and systematically practised in the first century CE. One reason for the systematic and large-scale recycling was probably the high demand for glass for everyday use as well as architectural purposes and the perfume industry that was flourishing in Pompeii at the time. The latter could possibly shed further light on the possible location of the glass factories in the vicinity of the perfume workshops in the south-western sector of the city or in the area of the temple of Venus and the nearby *horrea*. The few pieces of glass that ended up in the landfill represent the margin

of error of the municipal recycling system, but the figures clearly show that glass recycling was organically integrated into urban life. When the city was destroyed by the eruption of Mount Vesuvius, Pompeii was intensively engaged in the post-earthquake reconstruction and exploited all available resources to the full, including glass cullet.

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Geographical coordinates 40°44′52.46″N,
14°29′7.25″E.

The location refers to the centre of the trench excavated outside the building of the Sarno baths.

Authors contributions CB: designed and conceptualised the paper, selected and prepared the samples, took the photos of the glass finds, conducted the typological and technological study, interpreted the chemical and typological data, contributed to writing [introduction; materials and methods; results (Forming technique and typology, chemical composition); discussion; conclusions]. She prepared Figs. 3 and 4 and the supplementary information. GF contributed to the writing (Archaeological context), prepared Figs. 1–2 and contributed to edit and review the paper. He supervised the excavation in the field and performed phasing, analysis and interpretation of the sequence. NS performed the chemical analyses, interpreted and visualised the analytical data, contributed to the writing [Materials and methods; Results (chemical composition); Discussion], editing and review of the manuscript, and prepared Fig. 5. RR: contributed in term of research input, participated to edit and reviewing the paper, held the grant DNRF119 for Centre of Urban Network Evolutions and the project Circular Economy and Urban Sustainability from the Augustinus and Carlsberg Foundations. JB: contributed to edit and reviewing the paper. The University of Padova - Dept. of Cultural heritage funded the research project on the field and the elaboration of the data from the excavation. All authors read and approved the final manuscript.

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Data availability Data that support the findings of this study are provided within the manuscript and as supplementary information files

Declarations

Statements and declarations The authors disclose financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

Competing interests The authors declare no competing interests.

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