THE PRIMARY PRODUCTION OF GLASS AT HELLENISTIC RHODES

THILO REHREN, LINDSAY SPENCER AND PAVLOS TRIANTAFYLLIDIS

INTRODUCTION

Hellenistic Rhodes has long been acknowledged as a major manufacturing centre for consumer goods, such as those transported in Rhodian amphorae (Whitbread 1995), as well as luxury goods, including glass bowls and jewellery. This is based primarily on surviving artefacts, found throughout the eastern Mediterranean and Middle East and attributed to Rhodian production centres based on stylistic grounds (eg Triantafyllidis 2000). Impressive workshop evidence from the modern city of Rhodes attests to the making of large-scale bronze statuary during the Hellenistic period (Zimmer 1990).

The archaeological evidence for the working of glass is almost exclusively based on the material excavated in 1966–67 at the Kakoula Property by Gladys Davidson-Weinberg and Olga Kakavogianni of the 22nd Ephorate of Prehistoric and Classical Antiquities. This material comprises predominantly finished beads, and bead and vessel manufacturing debris, as well as thousands of centimetre-sized pieces of fresh cullet (i.e. fragments of newly-coloured glass rather than recycled vessel fragments) in a range of colours, from high-quality clear and gold glass, to red, yellow, purple and various blues. A specific corpus of this material includes ceramic trays covered with intensely coloured glass residue, thought to be trays in which glass was liquefied for working (Weinberg 1983). The cullet also comprises considerable quantities of uncoloured transparent 'aqua' glass as well as raw glass of the same colour but that appears opaque from inclusions and porosity. The particular nature of this opaque or waste raw glass stimulated the scientific investigation of a range of samples, thought to be representative of the raw and aqua glass present.

The archaeological context of this material is in the Hellenistic period (second quarter of the 2nd century BC: Weinberg 1983; Triantafyllidis forthcoming); however, it is clearly in a secondary position and no evidence for a furnace structure was found with the production remains.

The main aim of the investigation was to test the hypothesis that this waste raw glass may represent evidence for the actual making of raw glass, as opposed to the much more common working of glass, and to discuss whether this took place at Rhodes or elsewhere.

THE MATERIAL

This study focuses on the suspected waste raw glass fragments as possible indicators of the making of glass from its raw materials, as well as the chemical relationship between these raw glass fragments, the aqua glass and the coloured glass cullet worked on site. Two groups of samples were analysed: waste raw and aqua glass, and some pieces of coloured glass.

Waste raw and aqua glass are extremes of a continuous group of variable appearance, from opaque off-white ('waste raw glass') to translucent to fully transparent fragments ('aqua glass') with but a few inclusions and air bubbles. The colour is typically pale green to watery blue resulting from minor iron oxide levels and varying redox conditions in the melt; the term 'aqua' was chosen to reflect this range. Many of the fragments, particularly the more opaque ones, are heavily weathered, resulting in the formation of an outer zone of off-white colour, often several millimetres deep.

The shape of the aqua glass fragments includes a similar range as that presented by the coloured glass cullet (see below). The raw glass in particular includes larger pieces, some of which have one smooth surface, apparently fragments of cakes or slabs. The most significant of these latter pieces are two flat slabs, of about 150x200mm and 100x150mm in area, respectively, and 20–30mm thick (FIG. 1). Other pieces are up to 60mm thick. They are smooth on one side only, while the opposite side is rather rough and irregular. Larger pieces show a polygonal fracture pattern typical of shrinking glazes or drying mud. No edge is identifiable on any of the pieces, indicating that they are probably fragments of even larger cakes.

The coloured glass cullet comes in a range of colours, from the predominant dark blue to light blue, purple, opaque white, yellow, green, aqua and decoloured clear glass. The typical size of the fragments is from 1–10cms^2 with irregular morphologies. A quick inspection of the material yielded no evidence for any original surfaces; all pieces appeared broken on all sides. They appear generally of a reasonable to very good quality, with few stones and seeds present. We assume that this cullet represents freshly produced new glass rather than recycled material.

METHODOLOGY

The sampling concentrated on the waste raw and aqua glasses, trying to include very 'dirty', inclusion-rich samples as well as relatively clean transparent ones, and a few coloured pieces of cullet; the main study of the coloured and worked glass is being undertaken by Dr Helen Mangou from the National Museum in Athens.

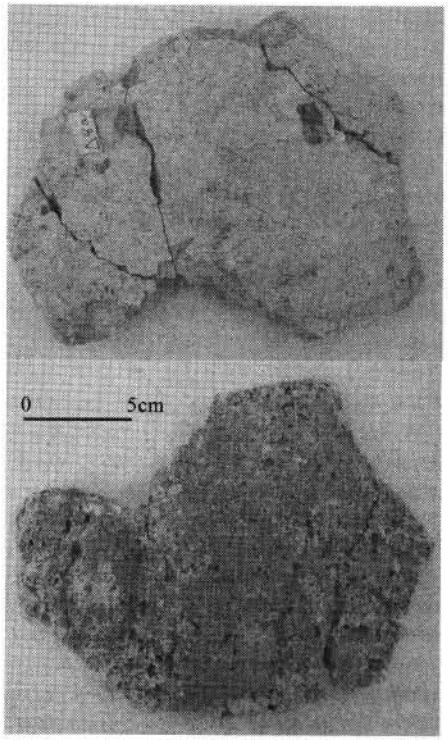

FIG. 1 Raw glass cake from Rhodes, Kakoula property. Top: upper side, bottom: lower side. The cake is 190mm long and *c.* 20mm thick

All samples were cut on site with a portable circular saw using a thin diamond-coated blade. The offcuts were mounted in cold-setting resin and then ground and polished following established metallographic procedures. The mounts were initially studied by optical and electron microscopy to establish the nature and distribution of any crystalline phases present. Particular emphasis was placed on their morphology, as a guide to distinguish between residual phases of the original batch material, and newly formed crystals grown from the cooling glass melt.

Chemical analyses of all glasses were then done using a JEOL electron microprobe analyser (JXA 8600 Superprobe) at the Wolfson Archaeological Sciences Laboratories at the Institute of Archaeology UCL. The analyses were done at full screen scans at 800x magnification, equivalent to areas of about 50 by 80 micrometers, to avoid sodium loss during analysis (see Shugar and Rehren 2002 for details). Areas free of any visible crystals or major porosity were selected in an effort to establish the composition of the pure glass phase rather than the bulk composition of glass plus crystal phases. Inevitably, some crystal phases or air bubbles may have been present just below the surface of the polished samples, therefore not visible in the electron image but still within the analysed volume; individual analyses with unusually low totals or extreme values for either silica or lime were excluded prior to averaging. The calibration of the superprobe was based on pure elements and simple compounds; oxygen was not measured but calculated based on stoichiometry. All data are reported as averages of about eight to twelve individual area analyses per sample, expressed in weight percent element oxides, except for chlorine. In the tables, the oxides are normalized to 100 wt% to facilitate comparison between samples; however, the original measured totals are given as well to indicate data quality. The accuracy of the calibration and validity of the ZAF correction procedures were tested by four repeat analyses of Corning A and B glass standards (TABLE 1).

RESULTS

The microscopic study of the waste raw glass demonstrated that the overwhelming majority of the crystalline material in the samples is quartz, with smaller amounts of a 1:1 silica-lime phase ('wollastonite'), and a few crystals of an as yet unidentified magnesia-rich phase, which is badly corroded and hence did not provide satisfactory analytical results.

TABLE 1 PUBLISHED VALUES FOR CORNING A AND B GLASS STANDARDS (CORNA AND CORNB), AND AVERAGES OF FOUR ELECTRON MICROPROBE ANALYSES OF THESE GLASSES DONE DURING THE ANALYSIS OF THE RHODES GLASSES (IOA A AND IOA B). BELOW THIS ARE THE ANALYSES OF FIVE DIFFERENT RAW GLASS SAMPLES AND THREE COLOURED PIECES OF CULLET (BLUE, PURPLE AND BLUE, RESPECTIVELY). EACH ANALYSIS IS THE AVERAGE OF SEVERAL AREA MEASUREMENTS AS DETAILED IN THE TEXT

Sample	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	MgO	MnO	Sb_2O_3	PbO	CuO	CoO	Total
CornA	67.1	1.00	1.09	14.30	2.87	5.03	2.66	1.00	1.75	0.12	1.17	0.17	100.0
IoA A	*67.2*	*0.97*	*1.00*	*14.72*	*2.82*	*5.05*	*2.68*	*0.98*	*1.49*	*0.07*	*1.12*	*0.15*	*98.7*
CornB	62.6	4.36	0.34	17.00	1.00	8.56	1.03	0.25	0.46	0.61	2.66	0.05	100.0
IoA B	*61.8*	*4.43*	*0.32*	*17.35*	*1.02*	*8.70*	*1.01*	*0.25*	*0.33*	*0.40*	*2.44*	*0.04*	*99.0*
Raw glass													
875	72.5	1.98	0.43	13.1	0.77	8.9	0.64	0.35	Bdl	0.20	Bdl	Bdl	96.4
876	72.2	2.01	0.45	13.2	0.70	9.2	0.65	Bdl	Bdl	0.34	Bdl	Bdl	99.4
881	72.1	2.51	0.46	12.0	0.70	10.3	0.79	Bdl	Bdl	Bdl	Bdl	Bdl	95.5
886	73.0	2.12	0.56	12.2	1.18	9.0	0.72	Bdl	Bdl	Bdl	Bdl	Bdl	95.9
891	72.3	2.42	0.35	11.7	0.65	10.8	0.65	Bdl	Bdl	Bdl	Bdl	Bdl	95.9
Average	*72.4*	*2.21*	*0.45*	*12.5*	*0.80*	*9.6*	*0.69*	*Bdl*	*Bdl*	*0.11*	*Bdl*	*Bdl*	
Coloured glass													
882	71.4	2.47	1.18	15.5	0.46	7.0	0.48	0.25	Bdl	Bdl	0.20	0.09	100.1
890	69.9	2.38	0.44	14.6	0.63	9.0	0.65	1.64	Bdl	Bdl	Bdl	Bdl	96.8
889	70.2	2.40	2.51	15.0	0.46	6.7	0.51	0.42	Bdl	Bdl	0.62	0.31	97.7

The quartz is present as well-rounded grains with evidence of chemical corrosion, such as rounded cavities and blending into the surrounding glass melt. Frequently, a carpet of tiny needles of silica crystals surround major quartz grains ('hedgehog pattern'). The latter phenomenon is particularly prevalent in areas with dense clusters of quartz grains, and is interpreted as indicating the saturation of the surrounding melt in silica and subsequent precipitation of SiO_2 (probably as cristobalite or tridymite) during cooling.

Wollastonite, in contrast, occurs more widely distributed and inevitably with sharp and well-developed crystal faces, indicating that it formed from the melt during cooling. Wollastonite is a typical intermediate phase in glass-forming reactions, and its presence in significant quantities indicates insufficient time and/or temperature during the glassmaking process to form a fully molten glass.

A few porous grains of chromium oxide were found in some samples, and interpreted as former chromite grains whose initial iron oxide content has been leached out.

The five analysed raw glasses all have a low-magnesia soda-lime-silica composition (TABLE 1). Neither typical colorants, such as cobalt or copper oxide, nor decolorants such as manganese or antimony oxide were found in any sample, with the exception of 875 which contains 0.35wt% MnO. The measured totals, of around 96 to 99wt%, are slightly lower than those obtained for the Corning A and B glasses; this is probably due to micro-porosity in the raw glass.

This composition is typical for soda–lime–silica glasses made from quartz and mineral natron; in particular the low levels of magnesia and potash are diagnostic. However, the levels of silica and lime are unusually high for Hellenistic and Roman SLS glass, and those of soda surprisingly low. The combination of surplus quartz, with further growth from the surrounding melt, and the high silica levels in the glass indicate that these samples were melted with insufficient flux present. Plotting the reduced base glass compositions (Rehren 2000) into the soda–lime–silica diagram (Shahid and Glasser 1971) places them onto the 1200°C isotherm on the slope towards the silica corner of the system (FIG. 2a). This indicates melt temperatures some 200 to 300°C higher than those obtained for other Hellenistic glasses (Spencer 2002; comparative data from Vergina, Olympia, Tel Anafa and Morgantina, all from Brill 1999). It is also consistent with the hedgehog pattern frequently observed in these samples, and the principles of the partial melting model as developed by Rehren (2000).

A few samples of coloured glass were also analysed by electron probe micro analysis. These show, within the overall low-magnesia soda-lime-silica formula expected of Hellenistic glasses, a wider range of compositions and colorants/decolorants than the raw glasses (TABLE 1), with, on average, slightly higher soda levels and somewhat lower silica and lime. However, when plotted into the soda-lime-silica diagram, they still fall onto the silica-rich slope of the system (FIG. 2b), with melting temperatures of around 1100°C.

Based on the limited data available so far, the transparent blue glass seems to be coloured by a combination of cobalt and copper oxide. The purple glass is coloured by manganese, and the opaque yellow and green glasses are coloured by lead antimonate and lead antimonate plus copper oxide, respectively, with somewhat elevated levels of iron oxide, but otherwise unchanged levels of minor oxides, and no detectable tin, zinc or arsenic oxide.

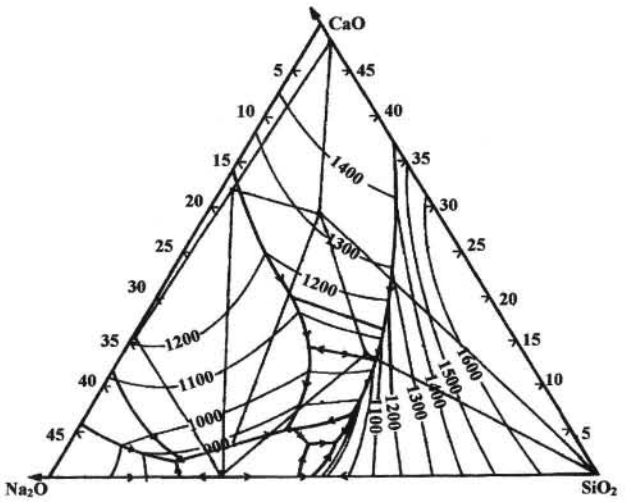

FIG. 2a Plot of raw glass analyses from the Kakoula Property. Data reduction according to Rehren (2000). Note the scatter along the 1200°C isotherm towards the silica corner of the system

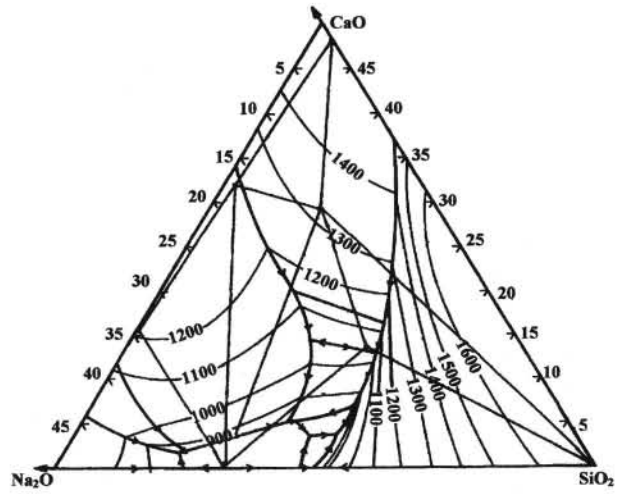

Fig 2b Plot of coloured glass analyses from the Kakoula Property. Data reduction according to Rehren (2000). The theoretical melting temperatures of these glasses are about 100°C lower than those of the raw glasses

INTERPRETATION

The raw or aqua glass contains almost no discernible additives such as colorants or decolorants, indicating that it is indeed freshly made glass rather than recycled cullet. Many pieces contain areas rich in relict quartz, rendering the glass opaque and unworkable. These fragments are of a shape different from most other samples, exhibiting a smooth top surface and a distinct fracture pattern. It is argued that these samples represent raw glass melted from quartz sand mixed with insufficient natron, resulting in a soda-deficient glass melt containing quantities of residual

quartz and newly grown wollastonite. This material is very similar in texture and composition to experimentally produced samples of partly melted glass batches (Shugar and Rehren 2002), and is interpreted as waste material from raw glassmaking. The scarcity of such material in the archaeological record is most likely due to either its deceptive nature when weathered, appearing almost like ordinary rocks, or to the efficient recycling in antiquity of this material. Recent ethnographic work on raw glassmaking in India indicates that only about half of the total glass produced in a given smelt is used straight away, the balance being intermediate or waste material of a kind apparently similar to the raw glass found at Rhodes. In India, this incompletely fused material is not discarded, but kept for remelting with the next batch of glassmaking (Sode and Kock 2001). The presence of some quantities of such material among the glassworking debris at the Kakoula Property at Rhodes therefore points to the local production of raw glass. Unfortunately, no furnace structures or fragments of raw glass with adhering furnace wall fragments have been found, severely limiting our ability to discuss the nature of these furnaces.

The composition of the coloured glass from the same complex differs from the raw glass in so far as it is less soda deficient and contains suitable amounts of colorants and decolorants. However, it is still much more similar to the Kakoula raw glass than to most of the published Hellenistic glass compositions used for comparison. Significantly, the coloured glasses from the Kakoula property plot on the silica-rich slope in the soda-lime-silica system, as opposed to the low-temperature region between the two eutectic troughs (see Rehren 2000 for a more detailed discussion of these eutectic troughs, and their significance for glass melt formation), which is occupied by the glasses from Tel Anafa, Olympia and Vergina (Spencer 2002). Only some of the Morgantina glasses plot also on the silica-rich slope of the system, at the 1000°C isotherm, relatively close to the Rhodes glass.

The apparent differences in melting temperatures indicated by the position of the glass compositions in the SLS diagram are not to be taken to represent true differences in the operating temperatures employed when making or working these glasses. The likely furnace temperature can only be taken from the diagram in the case of coexisting crystal phases under partial melting conditions (Rehren 2000; Shugar and Rehren 2002); thus, only the raw glass samples are suitable for this. The temperature indicated by their reduced composition, of around 1200°C, has in reality to be lowered by probably some 100°C to account for the effect of minor oxides which were included in the major oxide concentrations when processing the data. The temperatures obtained for crystal-free glasses, in contrast, are lowest estimates; while they too need to be corrected down to account for the minor oxides, the very fact that these samples have no or almost no coexisting crystal phases indicates that the actual furnace temperatures were likely to have been higher, due to the overheating necessary to obtain good-quality glass (Cable 1998). In effect, we may assume operating temperatures for the Rhodian glass furnaces of around 1100°C, consistent with estimated glassworking temperatures in antiquity elsewhere (Turner 1954).

Discussion

In the absence of any related furnace structures it is impossible to state with confidence that the raw glass debris was indeed produced locally. It could have been imported to Rhodes together with the glass cullet, as a poor-quality minority among otherwise good glass for the local object production. At present, however, this seems unlikely, particularly as the raw glass pieces are often significantly larger than the cullet fragments and would therefore not likely go unnoticed in a shipment of ready-made cullet. The occurrence of chromite grains in the waste raw glass may also indicate a local origin, as the Rhodian sands are known to contain this mineral, which is much rarer in sands from the Levantine coast (Whitbread 1995; Ian Freestone, pers. comm.). A further indication for the presence at Rhodes of at least some parts of the full *chaine operatoire* of glassmaking and working is the close compositional relationship between the raw/aqua glass and at least some of the coloured or decoloured glass from the same site, indicating that the raw or aqua glass was refined and coloured locally. To further test this hypothesis, however, one would have to study more of the glassworking remains; if the aqua glass composition is absent from the corpus of worked glass, then one has to assume that it was indeed only a semi-finished material used to produce either decoloured or coloured glass cullet for object production.

It is hoped that continuing work, including trace element and strontium isotope analyses, will eventually provide clearer evidence for the provenance of the raw materials. At present, the archaeological evidence seems to support the hypothesis of a local Rhodian glassmaking tradition, initially brought forward by Harden (1965) on purely stylistic grounds. It is hoped that the description of the waste raw glass will in the long term assist the identification of similar material from other glassmaking sites, both in the Late Bronze Age and the Hellenistic and Roman periods.

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**THILO REHREN AND LINDSAY SPENCER
Institute of Archaeology UCL
31–4 Gordon Square
London WC1H 0PY
UK
th.rehren@ucl.ac.uk

PAVLOS TRIANTAFYLLIDIS
22nd Archaeological Service of Dodecanese
Ippoton Street
85100 Rhodes
Greece