The Lycurgus Cup – A Roman Nanotechnology

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Introduction

The Lycurgus Cup (fig 1) represents one of the outstanding achievements of the ancient glass industry. This late Roman cut glass vessel is extraordinary in several respects, firstly in the method of fabrication and the exceptional workmanship involved and secondly in terms of the unusual optical effects displayed by the glass.

The Lycurgus Cup is one of a class of Roman vessels known as *cage cups* or *diatreta*, where the decoration is in openwork which stands proud from the body of the vessel, to which it is linked by shanks or bridges Typically these openwork "cages" comprise a lattice of linked circles, but a small number have figurative designs, although none of these is as elaborate or as well preserved as the Lycurgus Cup. Cage cups are generally dated to the fourth century A.D. and have been found across the Roman Empire, but the number recovered is small, and probably only in the region of 50-100 examples are known [1, 2]. They are among the most technically sophisticated glass objects produced before the modern era.

The openwork decoration of the Lycurgus Cup comprises a mythological frieze depicting the legend of King Lycurgus from the sixth book of Homer's Iliad. The figures, carved in deep relief, show the triumph of Dionysus over Lycurgus. However it is not only the cut-work design of the Cup that shows the high levels of skill involved in its production. The glass of the cup is dichroic; in direct light it resembles jade with an opaque greenish-yellow tone, but when light shines through the glass (transmitted light) it turns to a translucent ruby colour (Fig 1a and b).

The cup was acquired by the British Museum from Lord Rothschild in 1958 (with the aid of a contribution from the National Art Collection Fund) [3]. The mythological scenes on the cup depict the death of Lycurgus, King of the Edoni in Thrace at the hands of Dionysus and his followers. A man of violent temper, Lycurgus attacked Dionysus and one of his

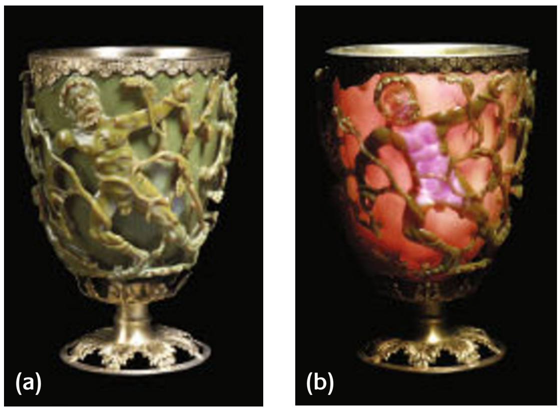


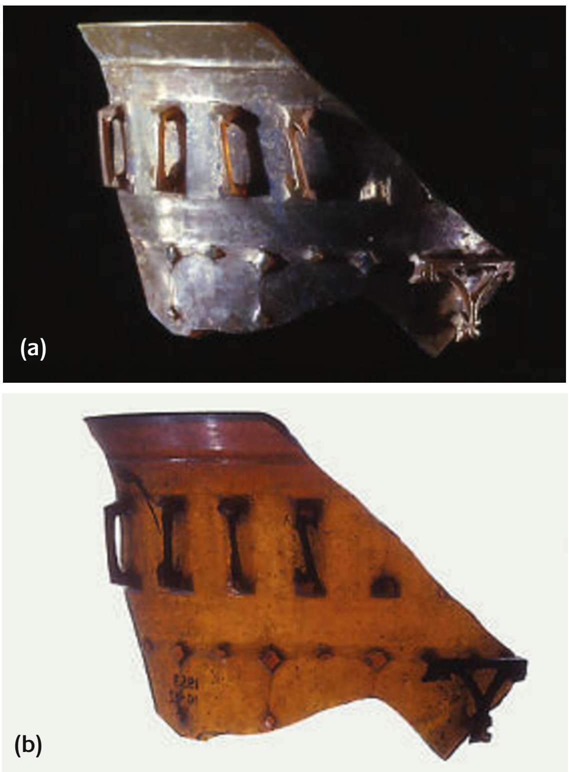
Figure 1 (a and b)
The Lycurgus Cup *1958,1202.1 in reflected (a) and transmitted (b) light. Scene showing Lycurgus being enmeshed by Ambrosia, now transformed into a vine-shoot. Department of Prehistory and Europe, The British Museum. Height: 16.5 cm (with modern metal mounts), diameter: 13.2 cm. © The Trustees of the British Museum*

Figure 2

The Lycurgus Cup *1958,1202.1, scene showing Dionysus instructing his followers to destroy Lycurgus. © The Trustees of the British Museum*

Figure 3 (a and b)

Fragment of diatretum *1953,1022.2 (h. 6.5 cm; d. 8 cm) in reflected (a) and transmitted (b) light. Department of Greek and Roman Antiquities, The British Museum. © The Trustees of the British Museum*



maenads, Ambrosia. Ambrosia called out to Mother Earth, who transformed her into a vine. She then coiled herself about the king, and held him captive. The cup shows this moment when Lycurgus is enmeshed in vines by the metamorphosing nymph Ambrosia, while Dionysus with his thyrsos and panther (Fig 2), a Pan and a satyr torment him for his evil behaviour. It has been thought that the theme of this myth - the triumph of Dionysus over Lycurgus - might have been chosen to refer to a contemporary political event, the defeat of the emperor Licinius (reigned AD 308-24) by Constantine in AD 324.

No precise parallels of this depiction of the myth exist but a number of versions of Dionysiac theme, related artistically or iconographically to the Cup, are known – in mosaic decoration, sculpture, coins and other decorated vessels [4]. According to Harden, the depictions that are perhaps the closest in terms of the drama of the scene are the Lycurgus and Ambrosia group in the centre of the frieze on the 2nd century Borghese sarcophagus (now in the Villa Taverna at Frascati) and the mosaic decoration in the apse of the *triclinium* of the 4th century Villa Romana del Casale at Piazza Armerina in Sicily.

The Lycurgus Cup is first mentioned in print in 1845 and is thought to have been acquired by the Rothschild family shortly afterwards, but the early history of the cup is unknown (as is the find spot) [5, 6]. However, no detailed study of the Cup was undertaken until 1950 when it was examined, at the request of Lord Rothschild, by Harden and Toynbee, resulting in their definitive article in *Archaeologia* in 1959. Because of the highly unusual colour and optical properties of the piece, there was initially some debate over whether the Cup was indeed glass as it seemed impossible, with the technical knowledge of ancient glass-working at the time, to produce such an effect. However, although noting that it exhibited a number of curious phenomena, Dr G. F. Claringbull, Keeper of the Department of Mineralogy in the British Museum (Natural History) concluded that it was made of glass (rather than opal or jade) [7], a result that was later confirmed in 1959 by X-ray diffraction [8].

Although now lost, due to breakage at some point in the past, the cup must originally have had an openwork base and may have had a taller rim [9]. The current silver-gilt foot with open-work vine leaves and the rim mount of leaf ornament are thought to date to the eighteenth or nineteenth centuries. On stylistic grounds, and also from the dates of comparative pieces (some of which are associated with more easily dated objects), the Cup has been dated to the 4th century AD. Harden and Toynbee suggested that it is probably of Italian manufacture, although they considered an Alexandrian origin also possible.

The colour of the Cup

The most remarkable aspect of the Cup is its colour. Only a handful of other ancient glasses, all of them Roman, change colour this way [10]; several of these are *diatreta,* with the more typical geometric decoration, but tend to show a less spectacular colour change (see Fig 3 a and b). It is therefore likely that the Lycurgus Cup was a special commission produced by a workshop which already made highly specialised and expensive glass products.

When the glass first came to scholarly attention in the 1950s the base, which had itself been added sometime in the early modern period to cover or repair earlier damage, was removed and some loose glass fragments from the original base were found (one showing signs of decoration but the other two being amorphous). Following preliminary study at the British Museum, including qualitative spectrographic analysis, the British Museum sent a sample in 1959 to the research laboratories of the General Electric Company Ltd (GEC) at Wembley for more detailed micro-analysis to try to determine the colorant [11]. Even at this stage, B.S. Cooper at GEC noted that the presence of trace quantities of gold, silver and other elements in the glass might be responsible for the complex colour and scattering effects of the glass and suggests that the colour may arise from "a combination of the "physical optical" colouration of colloidal metal in the glass plus, possibly, some pigmentation from metal combinations" [12].

Chemical analysis at GEC showed the glass to be of the soda-lime-silica type, similar to most other Roman glass (and to modern window and bottle glass) [13], containing in addition about 0.5% of manganese [14, 15]. In addition, a number of trace elements including silver and gold make up the final 1%. It was further suggested that the unique optical characteristics of the glass might be connected with the presence in the glass of colloidal gold. It was also noted that "to obtain the colouring constituents in the state necessary to give the remarkable glass its special qualities a critical combination of conditions was required during manufacture. These would be associated with the composition, including the presence of minor constituents, time and temperature of founding, chemical conditions during founding, and subsequent heat treatment. It is perhaps not altogether surprising that no other example of a glass having such unusual properties has come to light" [16]. Note that at that time, researchers were unaware of the handful of other examples of Roman dichroic glass that have since been recognised.

In the continuing quest to understand the remarkable colour effect, in 1962 a sample was sent to Dr Robert Brill of the Corning Museum of Glass, along with a sample of the diatretum shown in Fig 3a and b [17]. Work carried out by Brill, latterly in collaboration with GEC, on the Lycurgus Cup and diatretum samples (and on another example of dichroic glass) as well as on experimental glass melts confirmed that the dichroism was linked to the presence of minute amounts of gold (about 40 ppm) and silver (about 300 ppm) in the glass [18, 19]. However, simply adding traces of gold and silver to glass would not produce these unique optical properties and the critical factor was believed to be to be the formation of minute submicroscopic crystals or *colloids* of the metals. Colloidal systems can give rise to light scattering phenomena that result in dichroic effects. It was suggested that both the gold and silver contributed to the colour, the gold component being mainly responsible for the reddish transmission and the silver for the greenish reflection.

The work of Brill and GEC suggested that glass containing minute amounts of gold and silver had been heat treated, using suitable reducing agents, to produce colloidal metallic particles within the glass which resulted in the green-red dichroic effects. The colours produced in such a process would have depended upon the precise colloidal concentration and the particle diameter and are highly dependent on the proportions and oxidation states of certain elements, the time and temperature of heating and probably the atmosphere during heating [20].

Using the then available technology, Brill was unable to demonstrate unequivocally the presence of metallic particles. The relative contributions of silver and gold to the colourant effect, and whether the inferred metal colloids were a gold-silver alloy or separate particles of silver and gold, were unclear. Therefore, in the late 1980s, a further small fragment of the Cup was subjected to examination by Barber and Freestone [21]. Analytical transmission electron microscopy revealed the presence of minute particles of metal, typically 50-100 nm in diameter (see Fig 4). X-ray analysis showed that these nanoparticles are silver-gold alloy, with a ratio of silver to gold of about 7:3, containing in addition about 10% copper. The identification of silver-gold alloy particles confirms the earlier inference that the dichroic effect is caused by colloidal metal. In addition to these metallic particles, the glass was shown to contain numerous small particles (15-100 nm) that were shown to be particles of sodium chloride (see Fig 5); the chlorine probably derived from the mineral salts used to supply the alkali during the glass manufacture [22].

Of interest is the high gold to silver ratio of the alloy particles in the glass (c. 3:7) relative to the gold:silver (Au:Ag) ratio in the glass as a whole (c. 1:7). This is a reflection of the relative reduction potentials of Ag^+ and Au^+ and indicates that a substantial proportion of the silver remained dissolved in the silicate matrix after precipitation of the alloy particles. Recent work by Wagner and co-workers indicates that gold dissolves in glass in the monovalent form [23]. The reduction of previously dissolved silver and gold, during heat-treatment of the glass, will have caused the fine dispersion of silver-gold nanoparticles responsible for the colour. A key agent likely to have been involved in the redox reaction that reduced the silver and gold is the polyvalent element antimony, which is present in the glass at around 0.3%. Antimony was commonly added to glass in the Roman period, as both an oxidising agent (decolourant) and as an opacifier.

The fine particles of sodium chloride observed (fig. 5) are likely to have exsolved from the glass during the heat-treatment that caused the crystallisation of the alloy particles, but as they are colourless and their refractive index close to that of soda-lime-silica glass, their direct contribution to the

Figure 4
Transmission electron microscopy (TEM) image of a silver-gold alloy particle within the glass of the Lycurgus Cup [21]. © The Trustees of the British Museum.

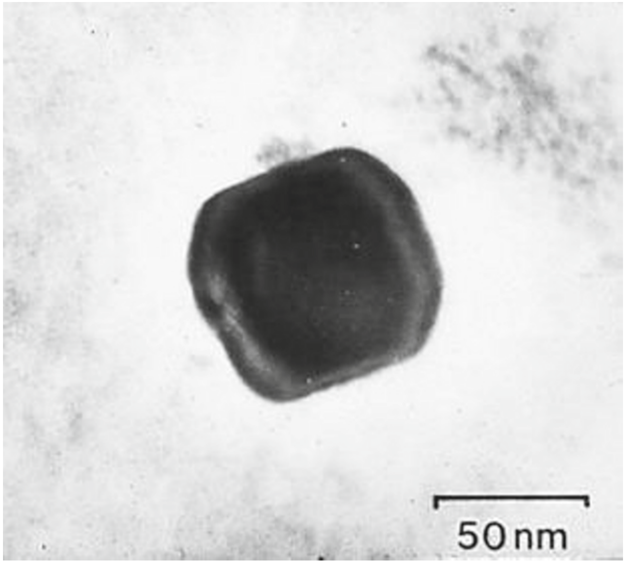


Figure 5
TEM image of sodium chloride particles within the glass of the Lycurgus Cup [21]. © The Trustees of the British Museum

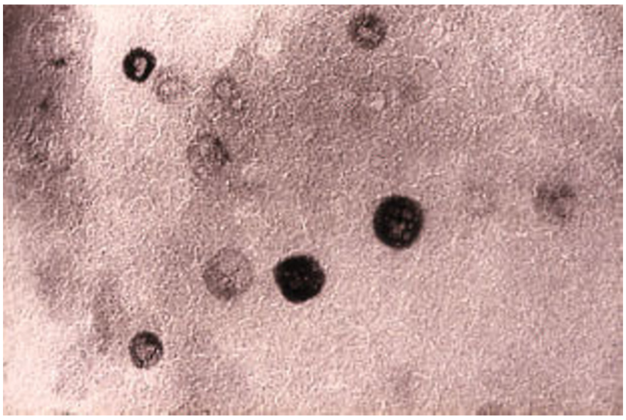


Figure 6 (a and b)
Glass blank made at the Corning Glassworks as a replica of the blank for the Lycurgus Cup in reflected (a) and transmitted (b) light . © The Trustees of the British Museum

colour of the glass is likely to have been minimal. However, halide additions have been found to promote the development of colour in gold ruby glasses [24] so it is possible that the sodium chloride in the glass indirectly contributed to its colour.

Fabrication of the Cup

The Cup and other cut cage vessels are generally considered to have been made by cutting and grinding the open work decoration out of a thick-walled blank of cast or blown glass, leaving small glass bridges linking the cutwork to the vessel [25]. It is believed that glass-makers (*vitrearii*) who made blanks were different from the glass cutters (*diatretarii*) who decorated and finished them. In their article Harden and Toynbee dismiss the view that the cage was carved from a separate blank and later joined to the inner vessel and cite Fremersdorf's article of 1930 as giving the best account of the manufacturing process for such vessels [26]. They also suggest that the hollows and borings behind the figures on the interior of the cup (discussed below) would also argue against the decorated Cup having been mould-blown. The Corning Glassworks produced a replica of the blank in the 1960s and this gives an impression of the nature of the original blank, which must have had walls about 15 mm thick (see Fig 6 a and b).

A number of replication studies have been based on this approach and, following a detailed examination of the surface of the Cup using low power microscopy, Scott suggested in 1995 that the Lycurgus Cup had been cut and polished using rotary wheels ranging from 6 to 12 mm in diameter [27-28]. However, more recently Lierke has suggested that many current assumptions about early glass working techniques are incorrect. In particular she has suggested that diatreta such as the Lycurgus Cup were not formed by cold cutting of glass blanks but by moulding [29-31].

This debate and recent research at the British Museum on the carving techniques of early semi-precious stones prompted an investigation of the cutting technique of the Lycurgus Cup at the Museum. The results of this study are summarised here but will be published in full elsewhere. The fragment of openwork (vine stem) found when the base of the Cup was removed was examined for traces of tool marks with a binocular microscope (see Fig 7) and a scanning electron microscope. The methodology adopted was based on that originally

Figure 7
Macroscopic photography of the cut-work fragment from the Lycurgus Cup in reflected light. © The Trustees of the British Museum

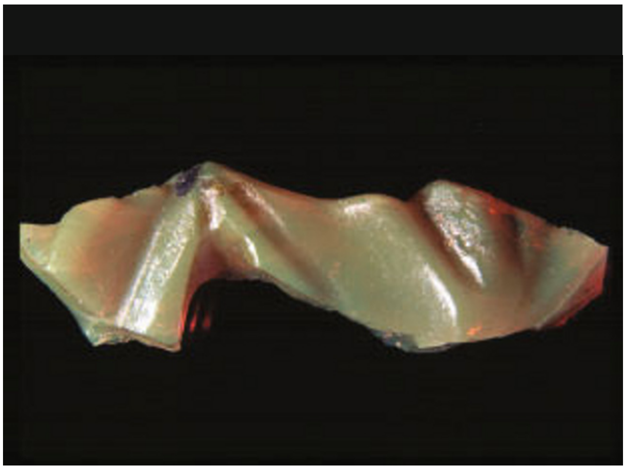


Figure 8
Backscattered electron image taken in the scanning electron microscope of the cut-work fragment from the Lycurgus Cup, showing the back surface of the fragment and the crescent-shaped cuts on the side, suggestive of rotary abrasion and polishing. © The Trustees of the British Museum

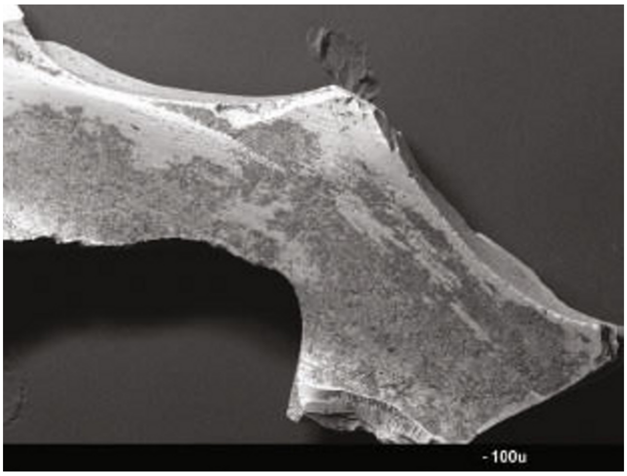
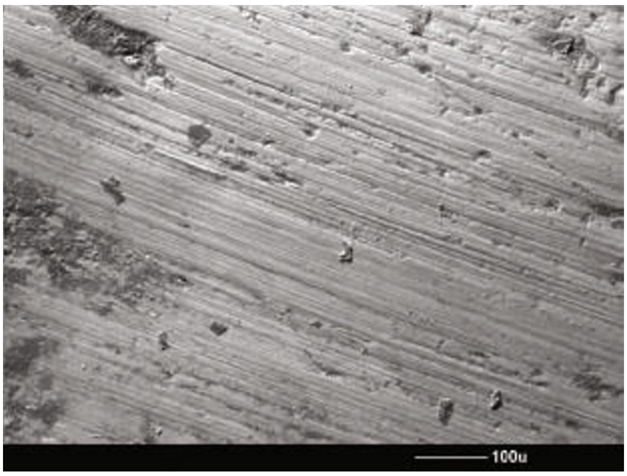


Figure 9
Backscattered electron image taken in the scanning electron microscope of the cut-work fragment from the Lycurgus Cup, showing coarse and fine abrasion striations on the back of the fragment. © The Trustees of the British Museum



developed by Sax, Meeks and Collon to investigate methods of stone engraving in the ancient world [32].

In the ancient Classical world, decorative gemstones of this type would have usually been worked using rotary methods of abrasion. Copper, bronze or iron wheels would have been attached to the end of a spindle, mounted on a lathe and rotated with a bow drill. Drills, both solid and tubular, as well as non-rotary saws and files were also used. Metal tools are too soft to have working surfaces themselves. They would have been charged with abrasive slurry, made by mixing a fine-grained abrasive sand, such as quartz or emery (corundum), with water or oil. These tools were then applied to wear away or 'cut' the stone [33]. Pliny indicates that Roman lapidaries used slivers of diamond to cut hard stones [34], but it seems likely that diamond abrasive would have only occasionally been available.

Examination of the open-work glass fragment showed that faint tool marks remain on most of the surfaces. The tool marks provide extensive evidence for mechanical abrasion and polishing not only on the outer surface but also on the sides and underneath the fragment. The sides of crescent-shaped cuts through the glass suggest the use of rotary abrasion and polishing (see Fig 8). In contrast, the front and the back of the open work appear to have been worked with non-rotary files and abrasives. The evidence for the mechanical removal of glass from the undercut back area of the fragment suggests that cutting and grinding rather than moulding of soft glass was the method of producing the lattice design (see Fig 9). The very highly polished surfaces of the fragment, once thought to have been fire polished, seems to have been produced purely by mechanical means as groups of regular fine parallel striations can be seen.

The skill of the craftsman consisted not only in the cutting of such an intricate design in such a fragile material, but also in the design and layout of the figures, and the advantage taken of the colour effects. For example, the body of Lycurgus is cut from an area of the glass which is a slightly different colour from the rest; as shown in figs 1a & b it is more violet in transmitted light and more yellow in reflection. In addition the glass inside the Cup and behind the bodies of the figures, which are not completely undercut, has been hollowed or bored out. This would have allowed similar amounts of light to pass through the bodies and the adjacent walls of the vessel so that the colour change was seen to maximum advantage [35].

The context of the Cup

Before the first century BC, glass had been a relatively uncommon material, and glass vessels were made in strong and often opaque colours. From the late first century BC, however, the new technique of glass blowing caused a revolution – colourless or weak blue-green vessels became widely used over a much wider cross-section of society. The mature Roman glass industry operated on a massive scale.

Glass was made in Egypt and Palestine in large tank furnaces which melted many tonnes of sand and soda at a time, and was distributed as raw lumps across the Empire where it could be remelted and made into artefacts. An illustration of the scale of glassmaking is provided by the Baths of Caracella, a major public building dating to the early third century A.D., which used some 350 tonnes of glass in wall and vault mosaics and windows [36, 37].

The Lycurgus Cup and the related vessels must be seen in the context of such a long-lived large-scale production of glass. The small number of cage cups represents a minute fraction of the total amount of glass in circulation at the time, and those showing so-called "dichroic" colour changes are a small fraction of this group. A limited number of other Roman-period glasses appear to have been coloured by gold, e.g. certain pinks in *opus sectile* panels from the Mediterranean region. Even the colours of the other dichroic glasses do not replicate the Lycurgus effect exactly. For example, the cage cup fragment shown in figure 3a and b is dichroic from opalescent buff on the surface to a clear brown in transmitted light. This vessel has a high silver content (2270 ppm) and only 13 ppm gold [36], so that the colourant effect is likely to be due to nanoparticles that are largely silver.

The Lycurgus Cup is therefore made of a very rare glass, and this glass seems to have been saved for a very rare type of vessel – a figurative cage cup. The execution of the openwork was carried out in a very skilful manner and must surely have been the work of a master lapidary. Even using modern power-driven tools, this type of vessel takes a great deal of time to complete [37-40]. Unlike the majority of glass of its time, the Cup, with its unique colour and decoration, must have been highly valued and intended for some special purpose. Remarkably, Whitehouse has drawn attention to a reference in the ancient literature which might well describe the Cup, or a similar vessel [41]. In his life of the third century pretender Saturninus, Vopiscus, who wrote in the early fourth century A.D., reports a letter supposedly written by Hadrian to his brother-in-law Severianus in Rome "I have sent you parti-coloured cups that change colour, presented to me by the priest of a temple. They are specially dedicated to you and my sister. I would like you to use them at banquets on feast days." Here then, is clear evidence that vessels that change colour were being made in the early fourth century (Vopiscus had seen them) and that they were prestigious items, worthy as gifts from the emperor to his close relatives. Furthermore, they were used on special occasions, on feast days. Whitehouse goes on to speculate that the change in colour from green to red symbolises the ripening of the grape, and that the depictions of vines on the Cup, as well as Dionysus, the Roman god of wine triumphing over Lycurgus, are strong evidence in support of this. Thus the Cup may have been specially intended for use at banquets dedicated to Dionysus.

The colour of the glass is therefore likely to be the reason for the creation of the Cup as it is seen, and is what provides its unique character. However, our understanding of the production of this glass is unclear. It seems very likely that, in the Roman period, the workshops which produced the "base" uncoloured glass, those that coloured the glass and those that carried out the cutting, were separate. Coloured opaque glasses were widely used in mosaics at this time, and it is likely that they were produced by a limited number of glass workshops which specialised in the colouring process, then sold on to mosaicists in the form of cakes, which could be broken up into the desired size. We can speculate that a colouring workshop produced one or more batches of glass coloured with gold and silver, recognised their importance, and sold them on to lapidary shops for cutting, perhaps in the form of blanks resembling that in Figs 6a and b. As some other cage cups are also coloured or have coloured cages, in blues, greens and yellows, it is possible that the workshop that made the Lycurgus glass was also supplying glass to the lapidaries who cut these.

It is clear that the colouring of glass using gold and silver was far from routine and something of a hit and miss affair. There were a large number of factors to control, including the overall concentration of the metals, their distribution and the time and temperature at which the glass was heat-treated [42]. It seems that not even the absolute and relative concentrations of gold and silver were easily controlled, let alone the distribution and growth of particles. Gold and silver concentrations vary widely between the few examples known [43], and even the colour of the Lycurgus blank was not homogeneous (see above). It is quite likely that the glassmakers were unaware that gold was the critical colourant, as most of these glasses are richer in silver. To introduce gold as a component of a gold-silver alloy (electrum) would make sense, as it would have allowed a more even distribution of the gold in solution. The addition of metals or metal oxides to colour glass was familiar to Roman glassmakers; for example, opaque red and brown glasses were produced by the addition of copper. Freestone et al. have speculated that the oxidised by-products of metallurgical processes ("dross", "slag" etc) were sometimes acquired to colour glass, and that this might explain how the "Lycurgus effect" was discovered [44]. It would also explain the relatively high levels of copper and lead oxides which are also present in the glass. However, there are a number of other possibilities which allow for the chance "discovery" of gold ruby, including accidents in the production of glasses with gold leaf decoration.

However the colouration of glass by gold was discovered, it appears that replicating gold ruby was a challenge to the Roman glassmaker; the technology was very restricted and does not appear to have outlasted the fourth century. While the production of red glass using gold is mentioned in medieval Islamic writings, examples of such glass have yet to be confirmed. Although the red "stained" glass of medieval church windows is sometimes suggested to be gold ruby, the colourant has been found to be copper in all cases so far analysed. The production of gold ruby on anything like a routine basis does not appear to have taken place until the seventeenth century in Europe, a discovery often credited to Johann Kunckel, a German glassmaker and chemist [45].

Conclusion

The Lycurgus Cup demonstrates a short-lived technology developed in the fourth century A.D. by Roman glass-workers. They discovered that glass could be coloured red and unusual colour change effects generated by the addition of a precious metal bearing material when the glass was molten. We now understand that these effects are due to the development of nanoparticles in the glass. However, the inability to control the colourant process meant that relatively few glasses of this type were produced, and even fewer survive. The Cup is the outstanding example of this technology in every respect – its outstanding cut work and red-green dichroism render it a unique record.

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Ian Freestone graduated in geology from the University of Reading and completed MSc and PhD degrees in geochemistry at the University of Leeds. Following post-doctoral work on silicate phase equilibria at the University of Manchester, he joined the British Museum in 1979, where he worked on the composition and production technology of inorganic artefacts from all periods and cultures. A recipient of the American Archaeological Institute's Pomerance Medal for scientific contributions to archaeology, he is President of the Association for the History of Glass. He joined Cardiff University as a professorial fellow in 2004, and is currently Head of Archaeology and Conservation. Address: Cardiff School of History and Archaeology, Cardiff University, Cardiff CF10 3EU, UK. Email: freestonei@cardiff.ac.uk

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Margaret Sax graduated in chemistry and physics at the University of London and started work in the department of Scientific Research at the British Museum in 1963. Working as a special assistant from 1979, Margaret's area of expertise is lapidary technology. Her research into the characteristics of tool marks preserved on stone artefacts has allowed her to develop a methodology based on scanning electron microscopy for the identification of ancient carving technique. She initially investigated the engraving of Mesopotamian quartz seals. In separate collaborative studies with Beijing University and the Smithsonian Institution, she is studying jades recovered from sites in China and Mesoamerica. In the present study, the methodology is applied to the glass openwork of the Lycurgus cup. Address: Department of Conservation, Documentation and Science, The British Museum, Great Russell Street, London WC1B 3DG, UK.
Email: msax@thebritishmuseum.ac.uk

References

1 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup', *Archaeologia*, Vol. 97, pp. 179-212 (the article includes in the appendix a catalogue of extant or lost but well authenticated cage cups and fragments known at that time)

2 Harden D.B., Hellenkemper H., Painter K. and Whitehouse D. (1987) *Glass of the Caesars*, Olivetti, Milan, pp. 245-249 (catalogue entry 139)

3 Harden D.B., Hellenkemper H., Painter K. and Whitehouse D. (1987) *Glass of the Caesars*, Olivetti, Milan, pp. 245-249 (catalogue entry 139)

4 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup', *Archaeologia*, Vol. 97, pp. 179-212

5 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup', *Archaeologia*, Vol. 97, pp. 179-212

6 Harden D.B., Hellenkemper H., Painter K. and Whitehouse D. (1987) *Glass of the Caesars*, Olivetti, Milan, pp. 245-249 (catalogue entry 139)

7 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup',

Archaeologia, Vol. 97, p. 180
8 British Museum Research Laboratory File 1144, letter dated 5.2.59 to Dr Mackey, Department of Physics, Birkbeck College, London
9 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup', *Archaeologia*, Vol. 97, pp. 179-212
10 Harden D.B., Hellenkemper H., Painter K. and Whitehouse D. (1987) *Glass of the Caesars*, Olivetti, Milan, pp. 245-249 (catalogue entry 139)
11 British Museum Research Laboratory File 1144, letter dated 11.6.59
12 British Museum Research Laboratory File 1144, letter dated 9.6.59 from B.S. Cooper at GEC
13 SiO_2 73.5%; Na_2O 13.0; K_2O 0.9; CaO 6.0; MgO 2.0; Al_2O_3 2.9; B_2O_3 0.1; MnO 0.5 (last 1% suggested to include traces of Fe, Ti, Ag, Au, Sb, Pb, Sn, Ba, Sr)
14 Chirnside R.C. and Proffitt P.M.C. (1963), 'The Rothschild Lycurgus Cup: an analytical investigation', *J. Glass Studies*, 5, p. 18
15 Chirnside R.C. (1965), 'The Rothschild Lycurgus Cup: An analytical investigation', *Proc 7th Internat. Cong. Glass, comptes rendus 2*. Paper 222, pp. 1-6; manganese is now known to be a common constituent of Roman glass and appears to have been used as an oxidising agent/ decolourant
16 Chirnside R.C. (1965), 'The Rothschild Lycurgus Cup: An analytical investigation', *Proc 7th Internat Cong. Glass, comptes rendus 2*. Paper 222, pp. 1-6
17 British Museum Research Laboratory File 1144, letter dated 20.11.62
18 Brill R.H. (1965) 'The chemistry of the Lycurgus Cup', *Proc 7th Internat. Cong. Glass, comptes rendus 2*. Paper 223, pp. 1-13.
19 Chirnside R.C. (1965) 'The Rothschild Lycurgus Cup: An analytical investigation', *Proc 7th Internat. Cong. Glass, comptes rendus 2*. Paper 222, pp. 1-6
20 Brill R.H. (1965) 'The chemistry of the Lycurgus Cup', *Proc 7th Internat. Cong. Glass, comptes rendus 2*. Paper 223, pp. 1-13.
21 Barber D.J. and Freestone I.C. (1990) 'An investigation of the origin of the colour of the Lycurgus Cup by analytical transmission electron microscopy', *Archaeometry* 32, pp. 33-45
22 Barber D.J. and Freestone I.C. (1990) 'An investigation of the origin of the colour of the Lycurgus Cup by analytical transmission electron microscopy', *Archaeometry* 32, pp. 33-45
23 Wagner F.E., Haslbeck S., Stievano L., Calogero S., Pankhurst Q.A. and Martinek K.-P. (2000) 'Before striking gold in gold-ruby glass', *Nature* 407, pp. 691-692
24 Kaminskaya N.L. (1980) 'Initiating the finishing process for gold-containing glasses', *Glass and Ceramics* 37, pp. 402-405
25 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup', *Archaeologia*, Vol. 97, pp. 179-212
26 Fremersdorf F. (1930), 'Die Herstellung der Diatreta', *Schumacher Festschrift*, Mainz, pp. 295 ff.
27 Scott G. (1993) 'Reconstructing and reproducing the Hohensulzen cage cup', *J Glass Studies* 35, pp. 106-118
28 Scott G. (1995) 'A study of the Lycurgus Cup', *J Glass Studies* 37, pp. 51-64
29 Lierke R. (1995) 'One more time - the making of the diatreta cups', *Glastech. Ber. Glass Sci Technol* 68, pp. 195-204
30 Lierke R. (1995) 'Vasa Diatreta. Teil II: Die Herstellung der romischen Glasnetzbecher', *Antike Welt* 26 (4) pp. 251-269
31 Lierke R. (1999) *Antike Glastopferei: Ein vergessenes Kapitel der Glasgeschichte Mainz*
32 Sax,M., Meeks,N.D. and Collon,D. (2000),'The Introduction of the Lapidary Engraving Wheel in Mesopotamia', *Antiquity* 74, pp. 380-387
33 Sax,M., Meeks,N.D. and Collon,D. (2000),'The Introduction of the Lapidary Engraving Wheel in Mesopotamia', *Antiquity* 74, pp. 380-387
34 Healy J.F. (1981) 'Pliny the Elder and Ancient Mineralogy', *Interdisciplinary Science Reviews* 6, pp. 166-180
35 Harden D.B. and Toynbee J.M.C. (1959), 'The Rothschild Lycurgus Cup', *Archaeologia*, Vol. 97, pp. 179-212
36 Stern, E.M. (1999) 'Roman glassblowing in a cultural context', *American Journal of Archaeology* 103, pp. 441-484
37 Price J. (2005) 'Glassworking and glassworkers in cities and towns', in A. MacMahon and J. Price (eds) *Roman Working Lives and Urban Living*: pp. 167-191. Oxford: Oxbow
38 Brill R.H. (1968) 'The scientific investigation of ancient glasses', *Proc 8th Internat. Cong. Glass, Sheffield*, pp. 47-68
39 Scott G. (1993) 'Reconstructing and reproducing the Hohensulzen cage cup', *J Glass Studies* 35, pp. 106-118
40 Scott G. (1995) 'A study of the Lycurgus Cup', *J Glass Studies* 37, pp. 51-64
41 Welzel J. (1998) 'Die Rekonstruktion eines Diatretglases nach einem Scherbenfund', *J Glass Studies* 40, pp. 127-139
42 Welzel J. (1999) 'Das Diatretglas aus Szekszard in Ungarn', *J Glass Studies* 41, pp. 153-165
43 Whitehouse D. (1989), 'Roman Dichroic Glass: Two Contemporary Descriptions?', *J Glass Studies*, 31, pp. 119-121
44 Badger A.E., Weyl W. and Rudow H. (1939) 'The effect of heat treatment on colour of gold ruby glass', *The Glass Industry* November 1939, pp. 407-414
45 Analyses of gold and silver contents of five dichroic glasses are provided by Brill R.H. (1968) 'The scientific investigation of ancient glasses', *Proc 8th Internat. Cong. Glass*, Sheffield, pp. 47-68
46 Freestone I.C., Stapleton C.P. and Rigby V (2003) 'The production of red glass and enamel in the Later Iron Age, Roman and Byzantine periods', in Entwistle C. (ed.) *Through a glass brightly - studies in Byzantine and Medieval Art and Archaeology* presented to David Buckton. Oxbow pp. 142-154
47 Hunt L.B. (1976) 'The true story of Purple of Cassius', Gold Bull. 9, pp. 134-139