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Composition and production of late antique glass bowls type Helle

Thilo Rehren [a,*], Marion Brüggler [b]

[a] UCL Qatar, a partner of Hamad Bin Khalifa University, Doha, Qatar
[b] LVR-Amt für Bodendenkmalpflege im Rheinland, Außenstelle Xanten Augustusring 3, 46509 Xanten, Germany

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ABSTRACT

Helle bowls are a particular type of late antique glass vessels found exclusively in continental northern Europe, both within and outside the Roman Empire. We analysed about one quarter of all known finds of this type using LA-ICP-MS, and several also using EPMA. The majority of the analysed bowls are made of HIMT glass, with a few consisting of Roman blue/green glass. Several bowls were found to be likely production pairs, defined as those produced from a single batch; most of these were found archaeologically together. We discuss recycling indicators such as elevated base metal oxides and increased potash and phosphate concentrations, arguing that all Roman blue/green glass in our assemblage is recycled, while about half of the HIMT glass appears to be freshly imported primary glass. The combination of archaeometric and archaeological evidence indicates that the glass workshop from Goch-Asperden (NW Germany) may have been one of the production sites for the bowls of this type; however, a wider production elsewhere cannot be ruled out.

1. Introduction

Late antique glass bowls of the type Helle, named after a site in Oldenburg, Lower Saxony (Werner, 1958: 387, 408f) and also known as Gellep 238 (Pirling, 1966: 153f) or Eggers 207 (Lund Hansen, 1987: 99 Type E 207), are rather rare. Helle bowls are recognisable even in small fragments by their almost bag-like body, an outturned and mostly downturned rim, a horizontal glass-trail wound around its upper part and seven to eleven pinched-out ribs on its lower part (Fig. 1). The glass trail usually has the same colour as the bowl itself, but one fragment from Asperden has a dark brown thread. The naturally coloured glass ranges from light green, light bluish green to light yellowish green and light olive; it can contain many bubbles or none at all. The size of the bowls varies gradually from a width of 7 cm and a height of 4 cm (cf. Table 1 no. 8, Inden-Pier) to a width of 13 cm and a height of 8 cm (Table 01 no. 2 and 28, Wijster and Bonn (currently kept in Tallinn University)).

The finish of the bowls varies, too. The bowls from Alfter, Bonn, Inden-Pier, the Rath Collection and Tournai (no. 1, 2, 8, 39, 32) all have a fire-rounded rim, while the bowl from Enns seems to have a cut-off rim (no. 37). The Enns and Tournai bowls also lack the glass trail on the upper part of the body (no. 37, 32). Some bowls have rather prominent, well pinched-out ribs (no. 3 Bonn, no. 6 HA 132, no. 7 HA 382, no. 9 Jülich, no. 29 Dalfsen), while the ribs on other bowls are comparatively flat (no. 1 Alfter, no. 2 Bonn, no. 13 Wachenheim, no. 22 Bennekom).

The type is dated to the end of the 4th century/around 400 AD and the first part of the 5th century (Böhme, 1986: 550; Werner, 1958: 389; Sablerolles, 1992: 33). At present, there are 87 bowls known, including uncertain fragments, from 39 sites from northwestern continental Europe (Table 1, Fig. 2; see also distribution maps in Sablerolles, 1993: 198 and Hermsen, 2003). The main area of distribution is northwestern Germany and the Netherlands, both within and outside the borders of the Roman Empire (for details of archaeological contexts cf. Brüggler and Rehren, submitted).

1.1. Helle bowls at Asperden

During the excavations of a late antique glass workshop in Goch-Asperden, NW Germany, fragments of 16 different Helle bowls were identified, including two misshaped objects and one fragment within the working layer of the later of the two excavated furnaces — both furnaces dating to a rather short time span around AD 400 or the first third of the 5th century (Brüggler submitted). The wall-fragments have a vertical rib and also – most of them – a horizontal glass thread. A further 12 rim sherds of bowls or cups were recovered in Asperden with an outturned and fire-rounded rim and seven more rim-sherds of bowls or cups have a tubular rim; some of these 19 exemplars might also have belonged to bowls of type Helle. Twenty-nine fragments of another eleven bowls have been found in the settlement at Gennep (Sablerolles, 1992), a few kilometres downstream from Asperden at the confluence of the rivers Niers and Meuse. Gennep was most likely a consumer site using the produce of the Asperden workshop. Taken together, the finds from Asperden and Gennep constitute around one third of the total currently known Helle bowls.

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[*] Corresponding author.
E-mail addresses: th.rehren@ucl.ac.uk (Th. Rehren), Marion.Brueggler@lvr.de (M. Brüggler).

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Fig. 1. Three bowls of type Helle, found in the Hambach Forest (left HA 382 = no 7, right HA 132 = no 6) and Jülich (centre) in the Rhineland. Width from left to right 11.5 cm, 13.5 cm, and 12.6 cm.
Photograph Jürgen Vogel, LVR-LandesMuseum Bonn

2. Research question and analytical approach

Against this background, several questions were developed concerning the production of these bowls. Firstly, we wanted to know whether the overall relatively small corpus of bowls can be linked to a single production workshop, based on their chemical composition. We then wanted to know whether the workshop in Asperden can be linked to the production of the bowls from Asperden, or indeed the whole series. To address these questions we had to determine to what extent the bowls are chemically consistent with each other so that they can be traced down to a single workshop, or even a single batch, as discussed, among others, by Price et al. (2005) and Freestone et al. (2009). The idea is that each batch of glass in a pot or small tank is homogenous within the analytical precision, but differs from the next batch. Thus, vessels produced from a single batch would be analytically indistinguishable from each other, but differ from similar vessels made either elsewhere or on a different day in the same workshop. We further had to determine the composition of glass worked at the workshop in Asperden, and compare this to the glass used in the Northern provinces more generally at the time when the bowls were made. Samples of Helle bowls were kindly provided by several different institutions in the Netherlands, Germany and Estonia, so that all in all 23 samples of the type could be analysed, more than a quarter of the entire population. For comparison, five pieces of working waste from the workshop in Asperden were also analysed, including vessel fragments (GOCH 196, 205), a moil (GOCH 228) and other waste (GOCH 238; 316).

All 23 samples were analysed by LA-ICPMS using an established protocol (Gratuze, 2013). The concentration of major and minor oxides of six of the samples was also analysed at the UCL Institute of Archaeology using Electron Probe Micro-Analysis. The results are in close agreement with the LA-ICPMS data. EPMA analyses of Corning B glass run at the same analytical batch confirmed the accuracy of the analyses within 5% relative for oxides above c 2 wt%, and within c 10% relative for minor oxides (Table 2).

A first assessment was done to test whether the five comparative samples from the workshop differed from the composition of the 23 Helle bowls, including four bowls from Asperden (HE ASP 1–4, Fig. 3). It became apparent that both find groups were chemically very similar; they are therefore considered together in the following presentation and discussion. The relevant sample numbers in the table facilitate an easy identification, where GOCH ### stands for the samples from the workshop in Goch-Asperden, and HE ### for the various Helle bowls; HE ASP 1–4 are from Goch-Asperden.

3. Results

The large majority of samples (23 out of 28) form a group characterised by more than 0.2 wt% titania, 1.0 to 1.6 wt% iron oxide, 1.3 to 2.4 wt% manganese oxide, and around 1 wt% magnesia (Table 3 upper part). Within this group a significant spread of concentrations in titania and iron oxide is note-worthy, as is the very close correlation of titania with the trace elements zirconium ($r = 0.96$, Fig. 4) and chromium ($r = 0.98$, omitting one outlying value of 105 ppm Cr_2O_3) and the good correlation with iron oxide ($r = 0.87$, Fig. 5). Iron oxide and alumina concentrations are also reasonably well correlated, with an r value of 0.83. In contrast, the concentration of lime (calcium oxide) is relatively narrow around 5.5 to 6 wt% and does not appear to be correlated with any of the other minor oxides. This major group of 23 samples includes 19 of the Helle bowls and four of the comparative samples from the workshop in Asperden.

The remaining five samples, comprising four Helle bowls and one light blue workshop sample, form a relatively homogenous second group with low levels of titania (below 0.15 wt%), iron and manganese oxide, and correspondingly lower concentrations of the trace elements zirconium, chromium and vanadium (Table 3 lower part).

The trace element data show a further separation into two groups, cutting across the separation identified above. Here, discriminating elements are the base metals copper, tin, lead and antimony as well as the minor oxides phosphate and potash. Thirteen of the samples (highlighted in Table 3 in bold) have significantly higher concentrations of these constituents than the remaining 15 samples (on average 500 ppm Sb compared to 4 ppm in the lower group; 280 ppm Cu compared to 66 ppm; 75 ppm Sn compared to 15 ppm). The elevated levels are found in all five samples of the minority group as well as in eight of the main group. Interestingly, the four samples of the workshop in Goch included in the main group are all low in base metals, while the one workshop sample from the minority group has also elevated base metal concentrations.

4. Interpretation

In all relevant criteria the main group is identical to HIMT glass, including the eponymous high levels in iron, manganese and titania, the latter reaching from 0.2 to 0.5 wt%, the positive correlation between alumina and iron oxide, and the constant lime levels around 6 wt% (Freestone et al., 2005). From the 4th century AD, this compositional group is found across the entire Roman Empire (Nenna, 2014), from Carthage (Freestone, 1994), Cyprus (Freestone et al., 2002) and Egypt (Rosenow and Rehren, 2014) via Bulgaria (Rehren and Cholakova, 2010), Italy (Mirti et al., 1993: Group E; Arletti et al., 2010) and France (Foy et al., 2003: groupe 1) up to Britain (Foster and Jackson, 2009). Diagnostic for this group are also higher concentrations of chromium, vanadium and zirconium compared to most other main compositional glass groups (Aerts et al., 2003).

The minority group of five samples with their relatively lower concentrations of the typical HIMT components is very similar to Roman blue/green glass (henceforth Rb/g), widely found in 1st to 3rd century AD Romano-British and other contexts (e.g. Jackson et al., 1991; Foster and Jackson, 2009). Glass of this composition and visual appearance is not only known from Roman Britain, but for instance also from Italy (Mirti et al., 1993: group B; Silvestri, 2008: group Ic1a and Ic1b) and Bulgaria (Kuleff and Djingova, 1999). Thus, this compositional group forms also one of the main glass groups which for several centuries were used across the Roman Empire.

4.1. Single batch pairs

Even though the majority of samples are from the same primary production group (HIMT) there is a relatively high level of variability within

Table 1
List of known bowls type Helle; bold: analysed samples.

	Country-State/Province, Location, context	Preservation	Colour	Remarks; height (H) and diameter (dm) in cm	Bibliography	Sample
1	**D-NRW, Alfter**	**1 bowl, put together**	**Yellowish green**	**Rim fire-rounded, indistinct ribs, trail begins with thick blob**	**Werner (1958), 408 List 2 Nr. 7, LVR-Landesmuseum Bonn Inv. 56.328**	**ALF 1**
2	**D-NRW, Bonn**	**1 bowl, fragmented**	**Light green**	**H. 8,2, dm. 13, rim fire-rounded, indistinct ribs, trail begins with thick blob**	**kept in Estonia, Tallinn University, Dept. of History, Inv. AI 3822:486, unpubl., pers. comm. A.-B. Follmann-Schulz/I. Krueger and Ain Mäesalu**	**TAL 1**
3	D-NRW, Bonn? grave?	1 complete		Hollow rim, prominent ribs	Doppelfeld (1966), Abb.177 below; Bonner Jahrb. 146, 1941, 428 and Taf. 86, 2; Förster 1931, 74 Nr. 310 and Taf. LXXXVIII	
4	**D-NRW, Castrop Rauxel, Erin, settlement**	**5 fragments of 5 bowls**	**ERI 1 and 2: green, ERI 3: yellow, ERI 4 and 5 light green**		**Fremersdorf (1970), 93 f.**	**ERI 1-ERI 5**
5	**D-NRW, Goch-Asperden, workshop**	**16 fragments of 16 bowls**	**ASP 1: green, ASP 2: yellow, ASP 3 + 4: yellowish green**		**Brüggler (forthcoming)**	**ASP 1-ASP 4**
6	D-NRW, Hambach Forest HA 132, male grave 49	1 complete	green	H. 6,3, dm 12,6, hollow rim, prominent ribs, beginning of trail thin	Brüggler (2009), 440.	
7	D-NRW, Hambach Forest HA 382, female grave 2	1 complete	Yellowish green	H. 6,3, dm. 11,5, hollow rim, prominent ribs, beginning of trail thin	Gaitzsch et al. (2000), 195. LVR-Landesmuseum Bonn Inv. 82.2093,02	
8	D-NRW, Inden-Pier WW 134, male grave 229 and female grave 255	2 complete		Grave 229 h. 5,4, dm 8,8-9,5 cm; grave 255: h. 4,2, dm. 6,9, both with fire-rounded rim	Pers. comm. W. Gaitzsch, A.-B. Follmann-Schulz, U. Geilenbrügge	
9	**D-NRW, Jülich, grave 2**	**1 put together, not complete**	**Green**	**Hollow rim, prominent ribs, beginning of trail thin**	**Groß and Heimberg (1975); LVR-Landesmuseum Bonn Inv. 72.412,02**	**JUL 1**
10	D-NRW, Kalkar-Altkalkar, Burginatium, auxiliary camp	1 fragment	Yellow-green		Unpubl., Excavation by the author, LVR-ABR, NI 2013/0071, St. 138-8	
11	D-NRW, Krefeld-Gellep, grave 713	1 complete	Green	H. 5,6, dm. 10,4, hollow rim, prominent ribs	Werner (1958), 408 List 2 Nr. 6; Pirling (1966), 153 f.	
12	D-NRW, Warendorf, settlement	1 fragment	light green		Grünewald (2010), 173 fig. 2	
13	D-RP, Wachenheim, grave	1 bowl, fragmented and put together	Light green	H. 5,7, dm. 12,6, hollow rim, very high neck, ribs low on the body and rather flat	unpubl., pers. comm. H. Bernhard	
14	D-NI, Flögeln-Eekhöltjen, settlement	probably type Helle	Light oliv green	Dm. 10,5	Erdrich (2002), 113	
15	D-NI, Gristede, settlement	2 fragments of 2 bowls	Light green; light blue		Erdrich (2002), 33.	
16	D-NI, Helle, grave 1 (warrior grave)	1 complete	Brownish green	H. 6, dm. 8, hollow rim	Werner (1958), 408 List 2 Nr.1; Erdrich (2002), 32.	
17	D-NI, Issendorf, grave	1 molten fragment (grave 2232) and a lost bowl	Green		Erdrich (2002), 169; lost bowl mentioned in Böhme (1974), 138.	
18	D-NI, Klein-Bünstorf, settlement	1 fragment	Light green		Erdrich (2002), 174.	
19	**D-NI, Mahlstedt, settlement**	**6 fragments of 6 bowls (?)**	**1 yellow, 2 bluish green, 1 yellowish green**		**Erdrich (2002), 52**	**MAH 1-MAH 4**
20	D-NI, Salzgitter, settlement	1 fragment			Erdrich (2002), 182	
21	D-NI, Tötensen, grave 444	9 fragments of 1 bowl	Light green		Erdrich (2002), 146	
22	NL, Gelderland, Bennekom, settlement	2 fragments		Ribs rather flat	van Es et al. (1985), 612	
23	NL, Gelderland, Didam-Aalbergen (Kollenburg), settlement	6 fragments of one bowl, 1 fragment, possibly 2 more.	Light greenblue	Dm. 9,5	Hermsen (2003)	
24	NL, Gelderland, Gennep	29 fragments of at least 11 bowls	7 yellowgreen, 1 light yellowgreen, 2 bluegreen, 1 olive green-yellow	Dm. around 9	Sablerolle (1992), id. 1993	
25	NL, Gelderland, Nijmegen, Broerstraat Grave 144	1 complete	Yellowish green	Hollow rim, prominent ribs, beginning of trail thin	Werner (1958), 408 List 2 Nr. 2	
26	NL, Gelderland, Nijmegen	1 complete	Light yellowish green	Hollow rim, prominent ribs, beginning of trail thin	Werner (1958), 408 List 2 Nr. 3; find-circumstances not clear	
27	**NL, Gelderland, Wehl-Hessenveld**	**3 small fragments**	**1 bluegreen (=WEH 1), 1 light green, 1 ?**		**Hermsen (2003), 16; and pers. comm. S. van Lith**	**WEH 1**

(continued on next page)

Table 1 (*continued*)

	Country-State/Province, Location, context	Preservation	Colour	Remarks; height (H) and diameter (dm) in cm	Bibliography	Sample
28	**NL, Drenthe, Wijster, settlement**	**7 fragments of at least 6 bowls**		**Rim fragment: h. 8, dm. 13, hollow rim**	**van Es (1967), 154 f.**	**WIJ 1**
29	**NL, Overijssel, Dalfsen, settlement**	**2 fragments of 1(?) bowl**		**Rim fragment: hollow rim; prominent rib**	**van Beek (1961), p. 46 fig. 7**	**DAL 1 + 2**
30	**NL, Overijssel, Deventer, Colmschate, settlement**	**3 fragments of 3 bowls, possibly 1 more**	**Light green**	**Rim fragment: hollow rim**	**Hermsen (2007), 199 f.**	**DEV 1-DEV 3**
31	NL, Overijssel, Heeten-Hordelman	1 fragment			Hermsen pers. comm.: not 100% sure; from an excavation	
32	B, Tournai, grave 2	1 bowl		Rim fire-rounded, no trail, ribs high on the body	Werner (1958), 408 List 2 Nr. 5, Böhme (1974), 304.	
33	B, Tongeren	1 complete	Olive	H. 5,4, dm. 8,3, rim fire-rounded	Werner (1958), 408 List 2 Nr. 4; Vanderhoeven 58 f. No 59, fig. 17.	
34	B, Montaigle	1 fragment			Hanut et al. (2012), 253	
35	DK, Hjoerring Amt, Oernboel-Hede, barrow	fragments of 1 bowl			Werner (1958), 408, List 2 Nr. 8	
36	F, Pas-de-Calais, Thérouanne	1 bowl		Without trail	Böhme (1974), 138	
37	A, Enns-Lauriacum, girl's grave 60	1 complete	Green	Rim probably cut off, no trail, ribs high on the body	Kloiber (1962), 66 f. and Taf. XXII	
38	GB, Brit. Museum, provenience unknown, "from Northern France and Rhineland graves"	1 complete	Yellowish green	Rim fire-rounded	Inv. (1900), 7-19,8. Werner (1958), 409, List 2 Nr. 11; Lasko (1971), 43, fig. 31	
39	Berlin, Staatliche Antikensammlung; disappeared after the II. World War; provenience unknown	1 complete bowl	Light green	H. 5, dm. 8,7, rim fire rounded, trail starts with thick blob	A. Kisa, Antike Gläser der Frau vom Rath (Bonn, 1899) N. 5. 155 u. Taf. 16, 137	

the compositional data. This provides a good basis to search for potential single-batch products or compositional twins. This was done by normalising the data to 1 million ppm, decorrelating the data using a principal component analysis and then performing a hierarchical cluster analysis of the principal component scores using the average linkage algorithm (pers. comm. M. Charlton 2015) (Fig. 6). In this presentation, samples with a high degree of similarity separate only at a very low height.

The dendrogram identifies several highly isolated samples, such as ERI 1 on the far left and GOCH 205 and MAH 4 on the far right. All three are HIMT glasses, but their extreme concentrations of base metals (ERI 1), HIMT indicators (MAH 4) or other criteria (GOCH 205) set them apart. The five samples on the left, from GOCH 316 to WIJ 1, form a distinct cluster separated at a high level from the remaining samples; these are the five Rb/g samples identified earlier. The remaining HIMT glasses fall into further cluster, with discriminating elements including the base metals (elevated in the cluster to the right, from ASP 1 to ERI 5) or relatively low barium concentrations (the central cluster from ASP 4 to DAL 2).

Three pairs of analyses separate only below a height of about 1 which we see as possible batch pairs, namely ERI 3 + 4; DAL 1 + 2; and TAL 1/ALF 1. The initial sampling was done with the intention to include fragments from different bowls. Following the identification of close chemical similarity for the two pairs from common findspots, we re-checked whether they could possibly come from single vessels. Following this, we are confident, based on differences in colour and appearance, that the individual samples in the pair from Erin are indeed from different vessels, while the two samples from Dalfsen (DAL 1 + 2) are potentially from a single bowl. This would be particularly interesting as it would provide a measure of the combined chemical heterogeneity and analytical uncertainty when analysing multiple samples from a single object, and therefore a benchmark for acceptable levels of difference when looking for batch pairs. It is important to note that the identification of possible batch pairs using hierarchical cluster analysis is providing slightly different pairs separating at these low levels depending on the algorithm used; further work is necessary to explore the potential and limitations of this approach.

The proposed pairing is particularly interesting in the case of TAL 1 and ALF 1 and appeared in all cluster analyses done so far; Alfter is a village bordering Bonn, and the bowl currently in the collection in Tallinn is said to be originally from Bonn. These two samples are clearly taken from different vessels, and their chemical similarity is therefore strong supporting evidence for their common production origin.

4.2. Recycling

About half of the analysed samples have strong indication for having been made using recycled glass cullet rather than fresh glass chunks from primary furnaces, as shown by the elevated levels of base metal concentrations (Jackson, 1997). Emphasis here is on 'elevated', which is a relative term. Any glass will contain certain levels of base metals as a result of their natural presence in the raw materials used. Here, we assume the following concentrations as geological thresholds: up to c 100 ppm Cu; up to about 75 ppm Pb; up to about 25 ppm Sn; and up to about 10 to 20 ppm Sb. These geological thresholds differ for different glass groups; the values given here are only a first approximation for HIMT glass. This topic is further explored in Foy et al. (2003: 46, 84); Foster and Jackson (2009: 196); Wedepohl et al. (2011); and Smirniou and Rehren (2013: 4734–5). Increased levels beyond the 'geological' threshold are most likely due to the inclusion of some coloured or decoloured glass into the cullet, such as broken vessels decorated with blue trails or blobs, or antimony-decoloured glass. The original levels of base metals in coloured glass, in the order of a fraction of a percent to a few percent for copper, and about half to two thirds of a percent for antimony in antimony-decoloured glass, would have been diluted in the bulk of recycled naturally coloured glass to such low levels as to be not noticeable visually, but still clearly identifiable by LA-ICPMS. A very crude mass balance estimate, using 2 wt% copper oxide in blue glass and an average value of 200 ppm of copper oxide in some of the samples with clear recycling indication, suggests that less than 1% of coloured glass would be sufficient to reach this level of copper oxide in the recycled batch.

Another indication for recycling is the presence of both manganese and antimony oxide in some of the samples, probably from mixing cullet of glass decoloured with either manganese or antimony oxide. This has been observed frequently in areas far from the primary production regions of those decoloured glass groups (Grünewald and Hartmann, 2015; Jackson and Paynter, 2015; Rehren et al., 2015), and is not surprising to be found here, too.

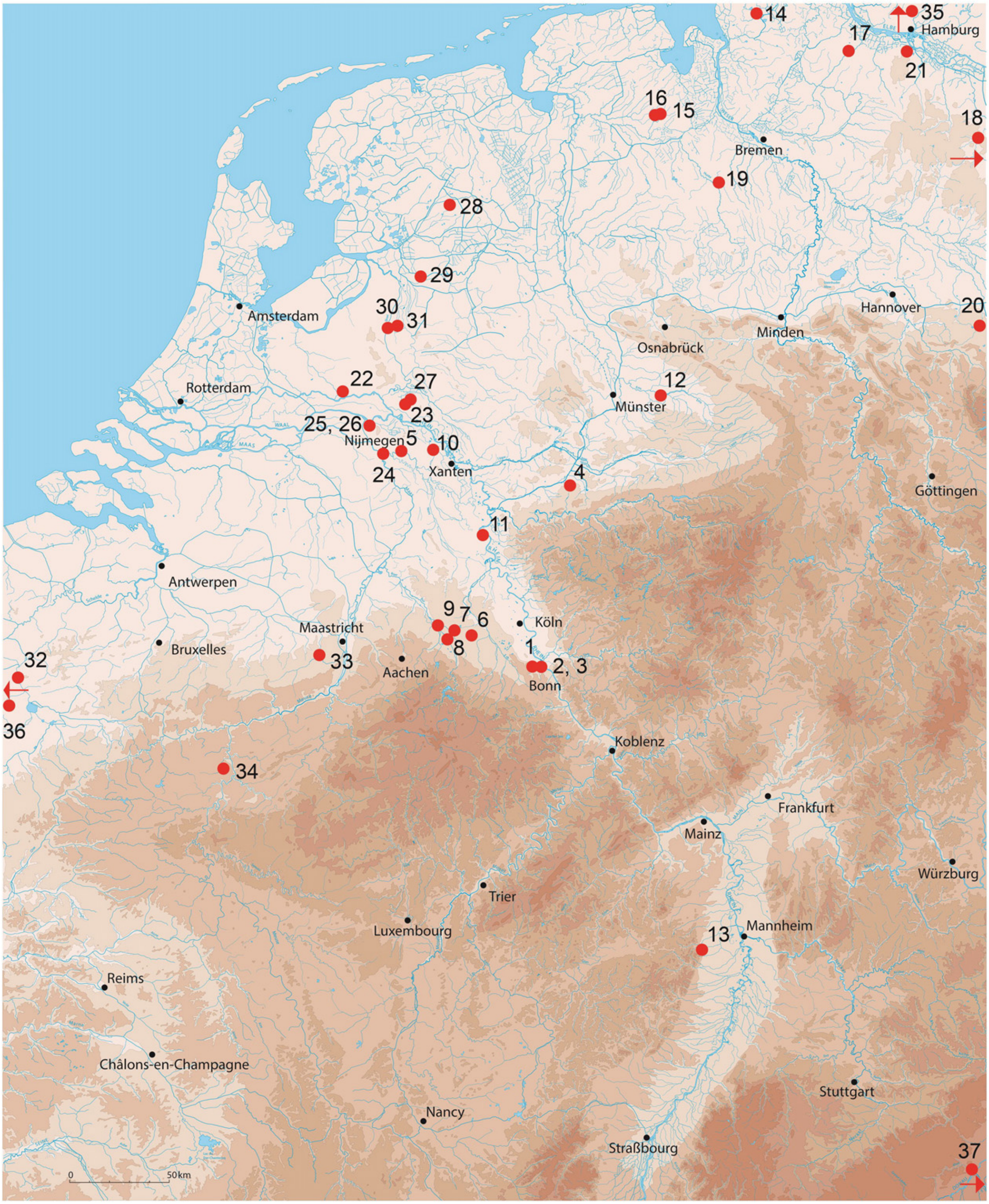

Fig. 2. Distribution map of bowls type Helle. See Table 1 for details on findspot numbers.
Graphic: Marion Brüggler (findspots) on a map by H.-J. Lauffer (LVR-Amt für Bodendenkmalpflege im Rheinland)

The pattern of occurrence of glass with recycling signatures among our samples is interesting. All five Rb/g glasses show strong indications of recycling, but none of the HIMT samples from the workshop in Asperden, and only less than half of the HIMT Helle bowls. This suggests that at the time of the production of the Helle bowls (very late 4th to first half of the 5th century AD) all Rb/g glass in the assemblage was heavily affected by recycling, while still more than half of the HIMT glass was fresh, i.e. unaffected by contamination through recycled glass. A further interesting observation can be made within this group of recycled glass (Fig. 7).

The Rb/g samples all show particularly high antimony levels, of around 1000 ppm Sb, compared to only c 200 ppm in the recycled HIMT glass, and less than 20 ppm in glass not contaminated. Fresh antimony-decoloured glass had in the order of 6000 to 7000 ppm Sb; an average level of 1000 ppm would therefore indicate around 10 to 15% of antimony-decoloured glass in the recycled material. We

Table 2
EPMA analyses of Corning B Reference glass as measured during the analysis of the Helle bowls (top five rows), compared to the published values (bottom row, Brill, 1999). Data in wt.%.

Cor B	SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3	FeO	MnO	TiO_2	P_2O_5	CuO	CoO	SnO_2	PbO	ZnO	Sb_2O_3	Sum
4	60.87	16.98	0.97	8.55	1.09	4.44	0.26	0.22	0.09	0.99	2.45	0.04	0.04	0.47	0.15	0.43	98.03
8	60.64	17.19	1.04	8.53	1.09	4.40	0.31	0.24	0.10	0.79	2.47	0.07	0.04	0.44	0.16	0.43	97.94
12	61.90	17.27	1.07	8.65	1.06	4.49	0.26	0.22	0.09	0.85	2.64	0.00	0.02	0.44	0.18	0.40	99.54
126	61.34	17.01	1.07	8.74	1.09	4.48	0.28	0.24	0.12	0.92	2.58	0.03	0.03	0.45	0.11	0.42	98.91
210	61.49	17.07	1.08	8.69	1.04	4.40	0.32	0.23	0.11	0.62	2.63	0.03	0.02	0.42	0.19	0.41	98.76
Ave	*61.25*	*17.10*	*1.05*	*8.63*	*1.07*	*4.44*	*0.28*	*0.23*	*0.10*	*0.83*	*2.55*	*0.04*	*0.03*	*0.44*	*0.16*	*0.42*	98.64
StDev	0.50	0.12	0.04	0.09	0.02	0.04	0.03	0.01	0.01	0.14	0.09	0.03	0.01	0.02	0.03	0.01	
Brill		*17.00*	*1.00*	*8.56*	*1.03*	*4.36*	*0.31*	*0.25*	*0.09*	*0.82*	*2.66*	*0.05*	*0.04*	*0.61*	*0.19*	*0.46*	

interpret this to indicate that the recycling was not indiscriminate, but that an effort was made to keep the lightly coloured, or nearly colourless glass such as Rb/g together with the antimony-decoloured glass, while the more strongly coloured HIMT glass was recycled separately. Such a careful separation of glass cullet, ready for recycling, is also evident from the Roman shipwreck found in the Adriatic, known as *Iulia Felix* (Silvestri, 2008; Silvestri et al., 2008), and can also be seen in the material from York in northern England (Jackson and Paynter, 2015).

The elevated base metal concentrations in the eight HIMT glasses coincide with higher concentrations of potash (on average 0.64 wt% compared to 0.47 wt% in the 15 HIMT glasses without elevated base metals) and phosphate (on average 520 ppm compared to 380 ppm) (Figs. 8, 9).

A similar trend can be seen for Rb/g glasses, even though there are no Rb/g samples here that do not show recycling indicators. The increase in both oxides can be readily explained as a result of the prolonged or repeated exposure of the glass to the fumes of the glass kiln during re-melting; the kiln gas is enriched in potash vapour and particulate phosphate, some of which is then absorbed by the liquid glass (Rehren et al., 2010: 75, based on the work of Paynter, 2008). In her experiments, done in collaboration with the Roman Glassmakers D. Hill and M. Taylor, she found an increase of the potash level in the glass from 1.6 wt% after 29 h of firing to 2.1 wt% after 54 h of continuous firing, that is an increase of 0.5 wt% within a day. The same effect can be seen in the formation of potash-based glass layers on the inside of kilns processing soda glass or lime-glazed pottery, as discussed elsewhere (Rehren and Perini, 2005; Rehren and Yin, 2012). Since the two effects, increased potash and phosphate and increased base metal concentrations, are materially independent but due to the same fundamental process (recycling) it is highly likely that their co-occurrence further confirms the proposed explanation for both of them.

4.3. Locating production

The heterogeneity of HIMT glass in general, and the likelihood that even a single workshop would have, over the course of a generation or two, processed glass of a range of compositions within the HIMT group, make it difficult to answer our main initial question whether all Helle beakers were made in one workshop. This is compounded by the fact that the material studied here straddles the period of transition from Rb/g glass to HIMT glass, adding further complexity to the range of glass compositions worked. The evidence from the workshop in Asperden shows that even a single workshop would have processed both fresh primary glass as well as recycled cullet, and of a number of different compositional groups. This is not unexpected for a relatively small workshop at the fringes of the Empire. Conversely, it is therefore also impossible to state or to exclude with any certainty whether all Helle bowls were formed in a single workshop, or in several. In theory they might well have been all produced at one site; however, even different workshops situated far from each other could equally have produced chemically very similar vessels, since they would still have worked more-or-less the same glass; a recent example for this is the occurrence during the 6th century AD of a particular glass composition in both southern France and northeast Bulgaria (Cholakova et al., in press).

A more promising approach to study the Helle bowls for their workshop identity would be to look at specific craft traits or workshop signatures (Cholakova, 2014). However, this is difficult to assess, since many of the listed examples are only small fragments and/or could not be investigated in the original in the course of this study. It is not quite clear, for instance, whether the occurrence of different rim finishes among the various Helle bowls is a chronological trait or points to different craftsmen producing these bowls. Rim fragments of various bowls from the workshop at Asperden include fire-rounded as well as tubular rims. It is not likely that all rims belonged to bowls of type Helle, but it shows that both variants seem to have been produced within a single workshop.

The distribution of the Helle bowls in the northwestern part of the Empire indicates a regional production origin. It is therefore prudent to look for major late antique glass workshops in the wider vicinity. A series of large glass workshops were found in the Hambach Forest, due west of Cologne (Gaitzsch et al., 2000), and two complete bowls were found in associated Roman tombs (Fig. 1). Two more were found in Inden-Pier – all four of them not sampled – and one in Jülich (JUL

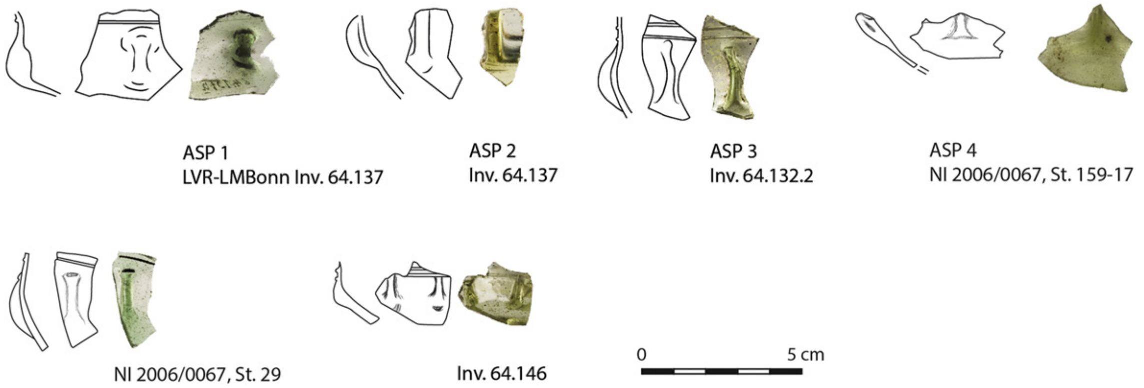

Fig. 3. Fragments of Helle beakers from Asperden. Top four fragments: sampled, bottom two fragments: not sampled.
Drawings and photograph: Till Könings (LVR-Amt für Bodendenkmalpflege im Rheinland)

Table 3
Chemical composition of Helle bowls (samples HE ###) and glass samples from the workshop in Goch-Asperden (samples GOCH ###). LA-ICPMS data; some minor oxides corrected to match EPMA data (see Table 2). For details of data processing and quality control see Supporting Online Material. Sample numbers in bold italic indicate likely batch pairs. Recycling indicators are in bold. Data in columns SiO_2 to Cl in wt.%, ZrO_2 to NiO in μg/g. The data is arranged based on the groups identified during the statistical analysis; see text for discussion.

number	SiO_2	Na_2O	CaO	K_2O	MgO	Al_2O_3	FeO	TiO_2	MnO	Cl	ZrO_2	P_2O_5	CuO	CoO	SnO_2	PbO	ZnO	Sb_2O_3	As_2O_3	BaO	SrO	V_2O_5	Cr_2O_3	NiO	Rb_2O	B_2O_3	Li_2O
HE ERI 1	66.6	18.5	5.9	**0.71**	0.91	2.7	1.44	0.30	1.30	0.9	150	**796**	**1126**	17	**282**	**1612**	**88**	**870**	12	565	454	39	36	20	8	161	6
HE MAH 1	66.3	19.4	5.6	**0.67**	0.84	2.6	1.17	0.31	1.56	1.0	148	**462**	**239**	11	**48**	**374**	**100**	**186**	5	726	467	35	38	14	7	172	8
GOCH 238	66.1	18.8	6.0	0.49	1.59	2.6	1.10	0.29	1.98	1.3	178	290	34	11	9	4	19	0	4	372	576	34	34	13	4	167	na
GOCH 196	67.1	18.3	5.7	0.38	1.04	2.8	1.38	0.40	2.15	1.1	213	399	81	11	19	36	24	6	5	312	488	47	53	17	4	183	na
GOCH 228	65.9	19.1	5.6	0.45	1.00	2.7	1.20	0.39	1.76	1.1	197	361	79	13	13	0	25	0	5	361	473	36	49	12	5	189	na
HE DEV 1	66.8	19.0	5.5	0.51	1.04	2.6	1.24	0.37	1.60	1.2	191	431	66	12	9	7	39	2	4	411	475	36	47	14	6	174	1
HE ASP 4	66.4	19.5	6.2	0.43	0.87	2.5	1.05	0.26	1.59	1.0	152	424	73	7	20	56	27	**28**	5	256	553	32	32	14	6	139	na
HE ASP 3	64.8	19.8	6.0	0.42	1.00	2.7	1.24	0.31	1.73	1.3	161	392	79	9	21	50	32	14	5	262	519	35	38	17	5	166	2
HE ERI 3	67.4	18.6	6.6	0.48	0.79	2.4	0.94	0.21	1.49	1.0	102	340	44	7	12	13	40	2	4	224	550	27	23	14	6	160	4
HE ERI 4	66.2	19.4	6.6	0.46	0.81	2.4	0.91	0.21	1.46	1.2	101	337	42	7	12	13	31	1	4	216	542	28	24	14	5	161	7
HE ASP 2	65.0	19.9	5.9	0.53	0.99	2.6	1.19	0.28	1.81	1.1	125	419	82	9	22	60	45	3	5	263	521	35	32	18	7	161	2
HE DAL 1	66.8	19.0	6.1	0.51	0.92	2.5	1.04	0.25	1.67	1.1	127	394	54	8	13	37	36	8	4	279	493	30	31	16	6	141	na
HE DAL 2	66.9	18.5	6.3	0.42	0.94	2.6	1.10	0.27	1.73	1.2	141	429	48	7	15	0	29	9	5	267	534	31	32	15	6	154	1
HE ALF 1	68.0	17.6	5.9	0.50	1.04	2.6	1.23	0.36	2.24	1.0	193	359	88	15	15	57	42	7	5	496	527	33	39	13	5	149	2
HE TAL 1	68.7	17.5	5.6	0.56	1.03	2.5	1.19	0.33	2.18	1.0	178	445	88	15	15	37	55	3	6	481	485	32	39	15	6	164	2
HE ASP 1	66.7	18.0	6.2	0.72	1.15	2.6	1.25	0.37	1.95	1.1	177	528	177	14	43	170	32	20	6	463	536	35	41	14	11	156	22
HE DEV 3	67.4	18.4	6.1	0.61	0.96	2.5	1.05	0.29	1.68	1.1	159	441	397	12	59	248	37	92	6	446	529	31	35	13	7	148	5
HE JUL 1	67.3	18.5	6.1	0.59	0.90	2.5	1.07	0.30	1.66	1.1	151	447	168	12	135	301	43	60	5	418	523	29	34	13	6	149	11
HE DEV 2	67.4	18.7	6.4	0.60	0.83	2.5	0.89	0.23	1.22	1.1	123	530	204	9	72	392	42	624	7	327	503	26	27	11	7	147	3
HE ERI 2	66.8	19.0	6.0	0.60	0.90	2.6	0.99	0.26	1.47	1.1	139	481	216	11	59	436	54	213	6	347	472	27	31	13	7	159	11
HE ERI 5	66.8	18.6	6.4	0.60	0.92	2.6	1.05	0.29	1.51	1.0	160	497	228	10	77	393	55	154	6	396	523	29	34	12	7	148	2
GOCH 205	68.1	18.5	4.7	0.37	0.94	2.6	1.13	0.31	1.33	1.1	166	300	55	11	8	4	20	1	5	660	450	36	105	10	5	151	na
HE MAH 4	65.3	18.7	5.7	0.52	0.83	2.8	1.63	0.52	2.44	1.1	284	385	83	13	15	26	49	5	6	866	487	62	66	20	7	123	1
Average	*66.7*	*18.8*	*6.0*	*0.53*	*0.97*	*2.6*	*1.15*	*0.31*	*1.72*	*1.1*	*162*	*430*	*163*	*11*	*43*	*188*	*42*	*100*	*5*	*409*	*508*	*34*	*40*	*14*	*6*	*157*	*5*
StDev	0.9	0.6	0.4	0.10	0.16	0.1	0.17	0.07	0.31	0.1	39	102	228	3	61	345	20	217	2	167	34	8	17	2	1	15	5
Rb/g glass																											
GOCH 316	71.6	16.7	7.1	0.71	0.50	2.54	0.41	0.08	0.53	1.0	47	1046	121	12	49	291	20	1146	3	225	454	14	13	10	9	145	na
HE WEH 1	71.5	16.8	6.7	0.74	0.51	2.56	0.52	0.10	0.41	0.9	44	882	98	7	37	200	37	1661	8	217	431	14	12	8	11	154	9
HE MAH 2	68.1	19.9	5.5	0.89	0.60	2.34	0.60	0.10	0.69	1.1	44	570	164	6	29	379	48	729	8	199	380	16	12	9	14	139	12
HE MAH 3	69.4	19.1	5.4	0.71	0.65	2.30	0.60	0.11	0.81	1.1	47	510	234	7	45	192	55	889	9	208	398	17	12	9	10	172	13
HE WIJ 1	69.7	18.3	6.0	0.67	0.69	2.41	0.69	0.11	0.87	1.0	46	491	298	9	40	305	43	832	10	245	423	17	12	9	10	164	16
Average	*70.1*	*18.1*	*6.1*	*0.74*	*0.59*	*2.4*	*0.56*	*0.10*	*0.66*	*1.0*	*46*	*700*	*183*	*8*	*40*	*273*	*41*	*1051*	*8*	*219*	*417*	*16*	*12*	*9*	*11*	*155*	*13*
StDev	1.5	1.4	0.7	0.09	0.08	0.1	0.11	0.01	0.19	0.1	1	250	83	2	8	78	14	374	3	18	29	2	0	1	2	13	3

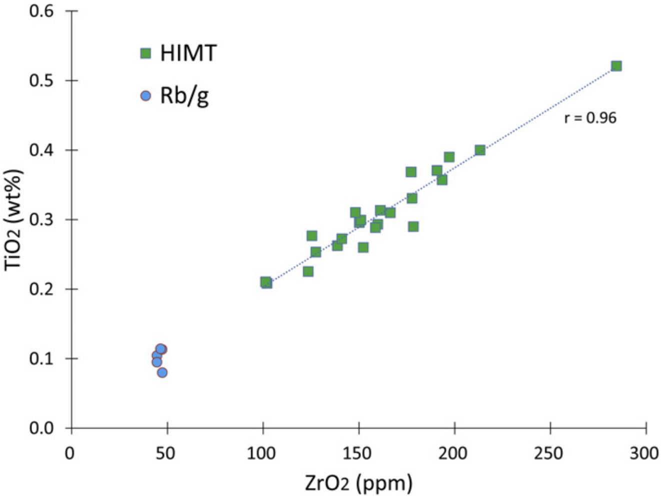

Fig. 4. Scatter graph of TiO_2 vs ZrO_2. TiO_2 vs Cr_2O_3 shows a similarly good correlation when omitting sample GOCH 205 which has an outlying value of 105 ppm for Cr_2O_3.

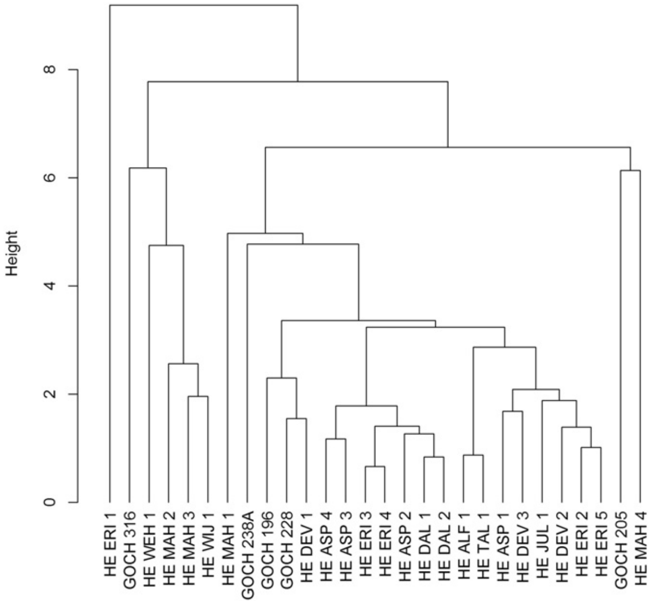

Fig. 6. Cluster dendrogram identifying samples of similar composition. See text for discussion; dendrogram generated by M. Charlton.

1) a few kilometres to the east of these glass workshops (cluster of find spots 6–9 in Fig. 2, representing 5 individual bowls). However, elsewhere we argue *against* a production relationship of the Helle bowls to the workshops in the Hambach Forest, based on the much more mixed and 'blurry' chemical signatures of much of the Hambach glass compared to the relatively tight correlation of the relevant oxide pairs in the Helle bowls, such as titania vs iron oxide (Grünewald and Hartmann, 2014; Brüggler and Rehren, forthcoming). Thus, the nature of the glass worked there differs sufficiently from the Helle bowl glasses analysed here to make it very unlikely that they were produced there. Instead, the cluster of five bowls on the distribution map within this region can also be interpreted as being linked to the Late Roman road connecting Cologne and the Channel Coast. Further to the west, the sites of Therouanne and Tournai are also situated along this road, and could have received their Helle bowls through long-distance trade or movement of goods or people.

In contrast, it is well possible that the workshop of Asperden was indeed (one of) the production site(s) for Helle bowls, even though the nature of the material does not allow a positive assignation. Looking at the distribution map, there appears to be a much stronger cluster in the Dutch Eastern River area, in the vicinity of Asperden (find spot 5) northwest of Xanten (find spots 10, 22–27), together representing at least 34 individual bowls, than in the Hambach Forest and its surroundings. However, we are not advocating a single production site for these bowls. The observed diversity in finish and detail of the Helle bowls would indicate that different workshops or at least different glass blowers within a workshop were making Helle bowls; a complete morphological and craft study of the vessels would be desirable to address this question in more detail, but is outside the remit of this paper.

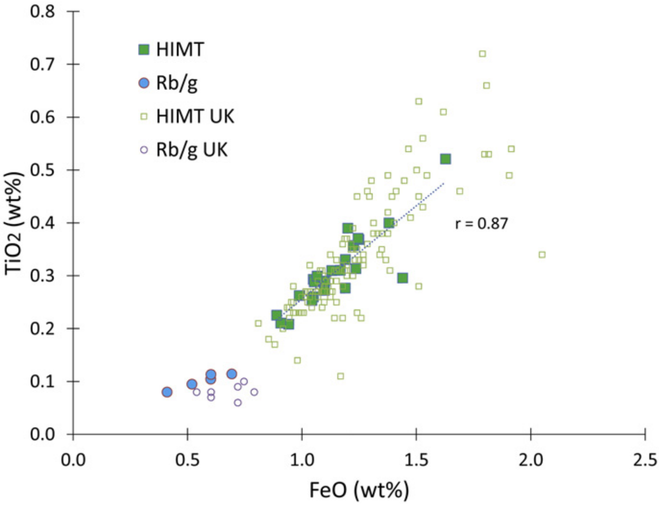

Fig. 5. Scatter graph of TiO_2 vs FeO. Omitting the sample ERI 1 (the sample most affected by recycling and hence with an elevated iron content likely due to contamination) would further increase the correlation coefficient (r value) to 0.95. Data for HIMT UK and Rb/g UK from Foster and Jackson (2009) are not included in the calculation of r.

5. Conclusions

Returning to the initial motivation for this study we can note that the Helle bowls are not compositionally homogenous, but were made using glass of two discrete compositions. Both can be equated with a high degree of certainty to well-known major glass compositions dominating the glass supply of the northern part of the Roman Empire during and immediately prior to the production of the Helle bowls. The majority are made of HIMT glass (19 of the 23 analysed fragments), and a minority of Rb/g glass (the remaining four samples). Both glass compositions

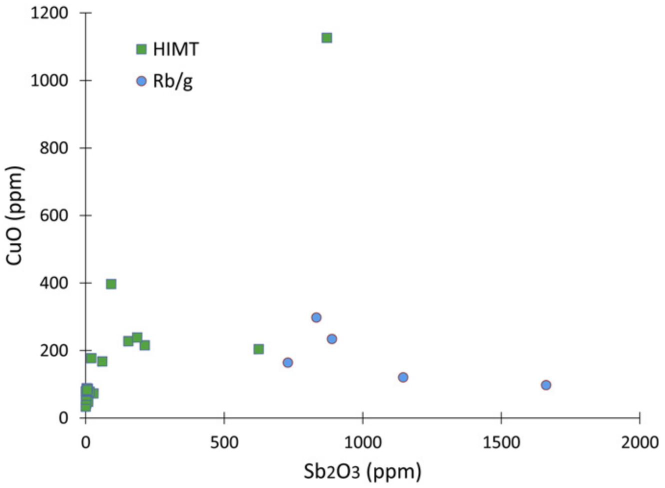

Fig. 7. Scatter graph of CuO vs Sb_2O_3. Values above c. 100 ppm CuO and c. 10 ppm Sb_2O_3 are seen as indicating recycling, and always occur together. See text for discussion.

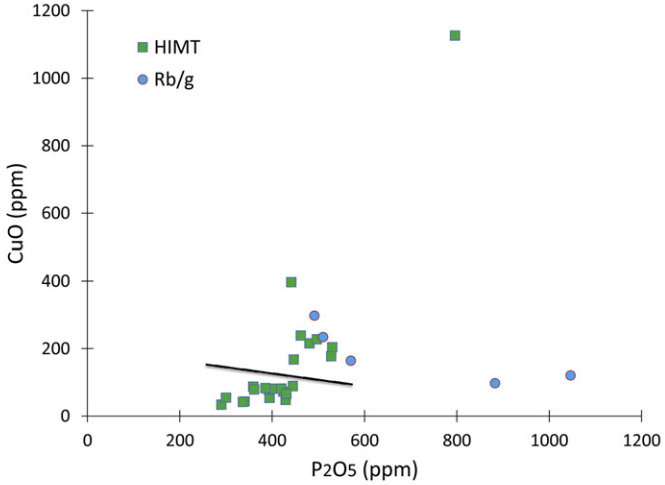

Fig. 8. Scatter graph of CuO vs P_2O_5. The black line separates glasses not or less affected by recycling (lower part, as indicated by their lower levels of CuO) from those more clearly contaminated by recycling (upper and right part).

are also present among the glass workshop material in Goch-Asperden, including vessel fragments and working waste such as moils and glass drips. Within the two discrete glass groups the composition of the Helle bowls varies relatively widely, in line with the variability of the major glass groups themselves, showing that they were not formed in a single large production event.

However, there are several pairs of Helle bowls that were most likely made from the same batch; two of these pairs were also found archaeologically together (the pairs in Erin and Dalfsen), while the find spots of the third pair are only recorded as “Bonn” and “Alfter”. While it is possible that the two samples from Dalfsen stem from one and the same bowl, the sample pairs from Erin and from Bonn (kept in Tallinn, Estonia) and Alfter, are definitely from separate bowls. The latter pair is also very similar in appearance, so their production origin from the same workshop is almost certain. A further bowl, from the Rath collection (Table 1, Nr 39), provenance unknown and not analysed here, appears also very similar with the two, since it has a fire-rounded rim and the trail starts with a thick blob. It is entirely possible that at least some of the pairs are in fact just parts of larger sets of multiples. These single batch pairs occurring together in one settlement site shed some light on the distribution process of the bowl type Helle. Assuming a production at least of some of the bowls in the glass workshops from Asperden, the pairs (or multiples) then seem to have been acquired together in *Germania secunda* before being brought to settlements as far away as in northern Germany and Denmark well outside the Empire, where they were used as drinking vessels and/or deposited in graves.

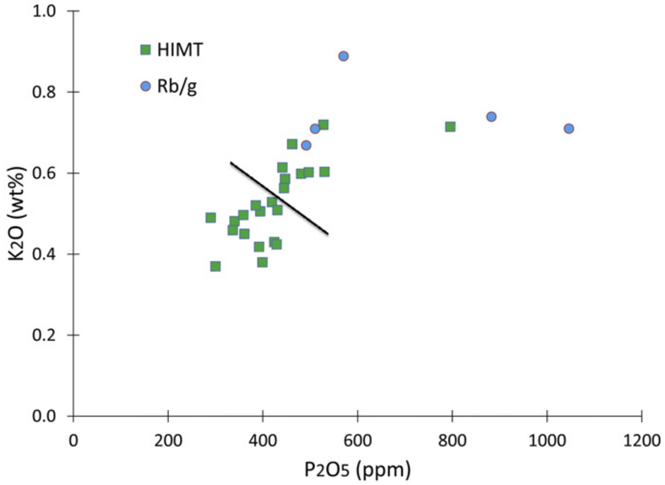

Fig. 9. Scatter graph of K_2O vs P_2O_5. The black line separates glasses not or less affected by recycling (lower part) from those more clearly contaminated by recycling (upper and right part), as indicated by their base metal content. The increased levels of K_2O and P_2O_5 are thought to be due to the prolonged exposure to the kiln atmosphere during remelting and recycling.

Overall the compositional data presented here is consistent with the historical setting of the region and the time of the production of the Helle bowls. By the end of the 4th century AD, that is when the first Helle bowls were made, fresh Rb/g glass would no longer have been available. It had been dominant in the Northern Provinces during the 1st to 3rd centuries AD, but by now any remaining stock would have been heavily affected by recycling and mixing with antimony-decoloured glass; this is reflected in the composition of the four Helle bowls made from Rb/g glass with their elevated antimony concentrations. In contrast, HIMT glass was very much current at this time, having made its first appearance only one or two generations before the bowls were produced; thus, there is both fresh HIMT glass available as well as already-recycled material. The elevated copper concentrations in the HIMT glass and the less elevated antimony levels indicate that this glass was contaminated more with copper-blue decoration than antimony-decoloured glass. Within this setting, the workshop in Asperden appears to have had good connections to the main glass-producing regions in the eastern Mediterranean (Gorin-Rosen, 2000; Freestone, 2006); all four HIMT-samples from the workshop are pristine, showing only the geological background levels of the relevant base metals and no elevated base metal, potash and phosphate concentrations. However, only one of the four analysed Helle bowl fragments from Asperden was made using fresh HIMT glass, suggesting that recycled glass cullet already made its way also to this workshop.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2015.05.021.

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