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Changes in glass consumption in Pergamon (Turkey) from Hellenistic to late Byzantine and Islamic times

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ABSTRACT

We present compositional data for nearly 100 glass samples from Pergamon, western Turkey, spanning 1500 years from the Hellenistic to Late Byzantine and Islamic periods. The data shows the use of already-known Roman glass groups during the first half of the time frame, for imported vessels as well as locally worked glass. No compositional change is seen related to the introduction of glass blowing for either of the glass groups in use during this time. During the first half of the 1st millennium AD, two previously little-known boron- and alumina-rich compositional groups emerge. These glass groups, thought to be regionally produced, dominate glass compositions in Pergamon during the mid-to late Byzantine and Islamic periods, indicating a major shift in glass supply and a fragmentation of the economy into more regional units. Plant-ash glass, from the 9th century AD replacing mineral natron glass in the Levant, plays only a minor role in Byzantine and Islamic Pergamon.

1. Introduction

For nearly two millennia, from 1000 BC to the late 1st millennium AD, glass making in the Eastern Mediterranean was based on mineral natron from the Wadi Natrun in Egypt. Little is known about Hellenistic glassmaking, with production evidence so far only known from Rhodes (Rehren et al., 2005, and references therein). At least from the Roman period it seems to have been concentrated in a relatively small area stretching from lower Egypt (Nenna, 2000; Nenna et al., 2005) to the northern Levant (e.g. in Bet Eli'ezer, Freestone et al., 2002a; Beirut, Kouwatli et al., 2008), where it was fused with local sand (Fig. 1). The glass composition directly reflects impurities in the sand used by each producer, resulting in chemically distinct glass groups (Freestone, 2005, 2006; Degryse et al., 2009). From these primary production centres the finished glass was then exported to the consumption centres for working into artefacts. Significantly, the various compositional groups have limited life spans, as documented from archaeological finds, suggesting that individual large-scale producers operated only for a few centuries before giving way to others.

Much of the literature concerning relatively early glass compositions (pre-5th century AD) is based on glasses from the northern and western provinces (e.g. Foster and Jackson, 2005, 2009, 2010; Paynter, 2006), and Italy (e.g. Mirti et al., 1993; Silvestri et al., 2005, 2008; Silvestri, 2008; Gallo et al., 2013). Here, dominating compositional groups include Roman blue/green glass (Rb/g), antimony-decoloured glass and manganese-decoloured glass, and HIMT glass. In contrast, much of the later analysed glass has been found in the Eastern Mediterranean, with dominating groups including Levantine I and II, HIMT, and more regionally restricted, Egypt I and II (e.g. Freestone et al., 2002b, 2008; Foy et al., 2003; Freestone, 2005, 2006; Nenna et al., 2005; Kato et al., 2009, 2010; Abd-Allah, 2010; Rehren et al., 2010; Rosenow and Rehren, 2014).

In contrast, and despite its economic and political importance and its closeness to the primary production centres, relatively little is known about the composition of glass used in Asia Minor. The analyses published up to now are predominantly from southwest Turkey; Brill (1999) lists some 35 analyses of glasses from Sardis and seven from Aphrodisias; Uhlir (2004; Uhlir et al., 2010) reports glass compositions for 106 glass samples from Hanghaus 1 in Ephesos, ranging from the 2nd century BC to the 6th and 7th

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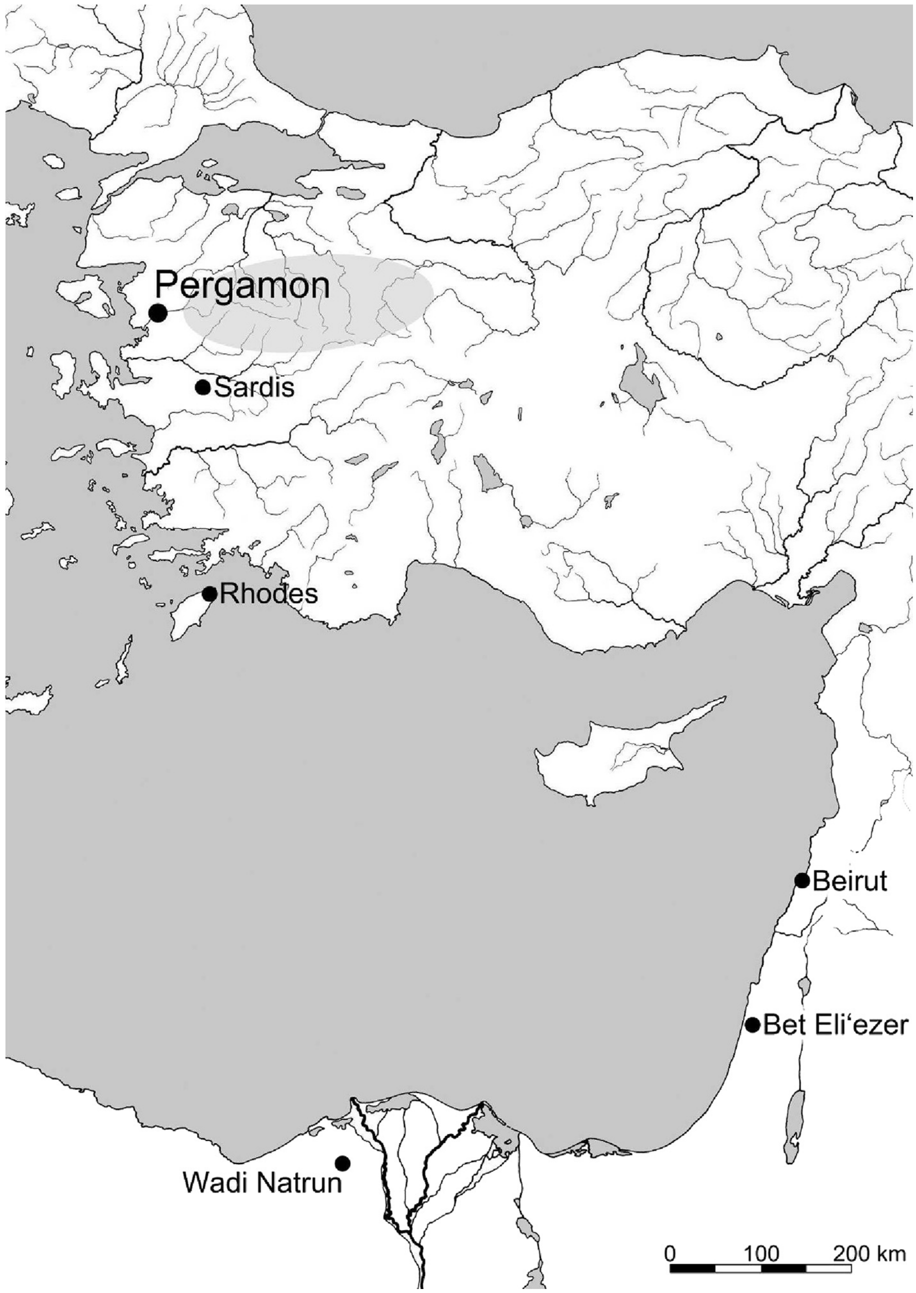

Fig. 1. Map of the Eastern Mediterranean with some primary glass production sites and the position of Pergamon and Sardis. The region of major borate deposits is shaded in grey, east of Pergamon. Drawing: Robert Dylka.

century AD; and Degryse et al. (2006) report 11 analyses of mid-1st millennium glass from Sagalassos in southern Turkey. This situation is corroborated by a similarly inadequate situation concerning typological studies of ancient and mostly Byzantine glass from Asia Minor, and stands in contrast to the cultural and economic importance and prosperity of the region. Only recently research concentrates on these aspects (e.g. Laflı, 2009). A comprehensive typological study of glass from Pergamon (Schwarzer, 2009; Schwarzer and Rehren, 2015; Schwarzer, in preparation) revealed a complex picture of imported and locally produced luxury glasses as well as every-day mass-produced vessels, and changing preferences for the use of glass as a medium to produce functional or decorative items of a wide spectrum. It also provided an opportunity to investigate the change in composition of the glass used in this important city, spanning more than 1500 years from the Classical era to the Islamic period.

1.1. Research aims

Long-term trends in the production, consumption and trade of glass in a particular site or region have so far been largely ignored by analytical studies. Fischer and McCray (1999) traced glass compositions at Sepphoris in modern-day Israel over more than a millennium, identifying a marked change in glass composition around the BC/AD turn which they link to the introduction of glass blowing and an associated adjustment of the glass recipe. A further major change occurred during the 8th to 9th century AD when glassmaking in the Levant reverted to plant-ash based recipes (e.g.

Kato et al., 2009, 2010), possibly due to an interruption in the production of mineral natron (Whitehouse, 2002; Shortland et al., 2006).

The assemblage from Pergamon is of particular significance not only due to the city's importance, but also because it encompasses both these major developments which may have had an influence on the nature of the glass worked and consumed in Pergamon. The earliest samples pre-date the invention of glass blowing, while the latest samples post-date the introduction of plant-ash based glass making in the Levant and Egypt. We want to see on a qualitative level how these events may have affected glass use in Pergamon, and what the Pergamenian assemblage tells us about the wider validity of the observations made in the earlier studies. Other major political changes, such as the schism of the Roman Empire, are not thought to have influenced glassmaking and glass use, while different levels of prosperity enjoyed by the city's inhabitants clearly influenced the quality and quantity of glass consumption (Schwarzer, 2009).

1.2. *Pergamon*

Pergamon, one of the most important cities in antiquity, is situated near the western coast of modern Turkey (Radt, 2011). The earliest settlement on the acropolis hill goes back at least to the Late Bronze Age, and prospered during the Archaic and Classical periods. The city obtained supra-regional significance with the Hellenistic dynasty of the Attalids who made it the capital of their kingdom. In the 2nd century BC during the reign of king Eumenes II this realm comprised a major part of Asia Minor. In 133 BC the kingdom was bequeathed by the last ruler Attalos III to the Roman people, and became part of the new province of *Asia*. Pergamon remained a powerful metropolis and prospered in the Roman Imperial period, especially during the 2nd century AD. With the division of the Roman Empire in the late 4th century AD the city became part of the Byzantine realm. Since then Pergamon became less important; however, the seat of a bishopric was established here and several churches were erected. In 716 AD the city was sacked by the Umayyads who enslaved the inhabitants. This dramatic event led to an interruption of the settlement up to the 10th century AD. Widespread building activities took place again in the middle/late Byzantine period (12th/13th century AD), mostly culminating in a spacious fortification. In the early 14th century AD the city was conquered by the Seljuks and then absorbed into the Ottoman Empire. Parts of the archaeological site of Pergamon, especially the lower city, are now covered by the modern city of Bergama, home to more than 60,000 people.

2. Materials and methods

The long-term excavations in Pergamon conducted by the German Archaeological Institute have yielded many thousands of glass fragments, from almost all periods of the city's history. During cataloguing these finds, 100 small samples were taken from a cross section of the material found in the so-called Stadtgrabung on the southern slope of the acropolis hill and with the permission of the Turkish authorities exported for chemical analysis; of these, 96 were artificial glass, one obsidian, one quartz, one a faience bead, and one fused ceramic. Sampling intended to cover all visually and typologically defined main types of glass (Schwarzer, 2009; Schwarzer and Rehren, 2015; Schwarzer, in preparation), as well as some extraordinary pieces, covering the entire chronological sequence present. The material chosen includes glass vessels, worked in different techniques (core-formed, mould-formed, free-blown and mould-blown) and different colours, window panes, jewellery and unformed chunks. As a result, the samples represent

Table 1
Comparison of EPMA and LA-ICPMS analyses of Corning reference glasses. Corning A and B were measured at the UCL Institute of Archaeology together with the Pergamon samples. Published values after Brill (1999) and Vicenzi et al. (2002). Each of the four individual measurements reports the average of five area analyses done on the glass. The LA-ICPMS analyses were done at Orleans, and are reported against trace element values from Brill (2012).

	SiO_2	Na_2O	CaO	K_2O	MgO	Al_2O_3	FeO	TiO_2	Sb_2O_5	MnO	CuO	CoO	SnO_2	PbO	NiO	ZnO	BaO	SrO	P_2O_5	Cl	SO_3	Total
Corning A	67.6	14.4	4.96	2.79	2.61	0.90	0.92	0.81	1.69	1.03	1.15	0.17	0.17	0.05	0.03	0.03	0.53	0.13	0.11	0.09	0.15	100.3
EPMA UCL	67.4	14.2	4.91	2.78	2.59	0.87	0.88	0.81	1.69	1.00	1.16	0.16	0.18	0.07	0.01	0.03	0.50	0.17	0.11	0.09	0.13	99.8
	67.8	14.3	4.95	2.77	2.64	0.89	0.95	0.83	1.69	1.01	1.20	0.15	0.17	0.05	0.01	0.02	0.55	0.16	0.11	0.09	0.15	100.5
	67.7	14.5	4.97	2.76	2.59	0.89	0.93	0.81	1.72	1.03	1.10	0.17	0.16	0.09	0.01	0.03	0.47	0.14	0.10	0.10	0.13	100.3
Average	**67.6**	**14.4**	**4.94**	**2.77**	**2.61**	**0.89**	**0.92**	**0.82**	**1.70**	**1.02**	**1.16**	**0.16**	**0.17**	**0.06**	**0.01**	**0.03**	**0.51**	**0.15**	**0.11**	**0.09**	**0.14**	**100.2**
Published	*66.6*	*14.3*	*5.03*	*2.87*	*2.66*	*1.00*	*0.98*	*0.79*	*1.75*	*1.00*	*1.20*	*0.17*	*0.23*	*0.10*	*0.02*	*0.05*	*0.47*	*0.14*	*0.13*	*0.09*	*0.13*	*99.7*
Corning B	62.7	16.8	8.64	1.01	1.06	4.13	0.29	0.11	0.44	0.25	2.66	0.04	0.03	0.46	0.09	0.16	0.11	0.02	0.83	0.17	0.50	100.5
EPMA UCL	62.7	17.2	8.50	1.02	1.05	4.08	0.29	0.10	0.42	0.25	2.64	0.06	0.00	0.52	0.09	0.17	0.09	0.05	0.70	0.17	0.52	100.6
	62.6	17.1	8.57	1.03	1.03	4.07	0.32	0.11	0.38	0.24	2.55	0.05	0.01	0.50	0.11	0.12	0.12	0.07	0.74	0.17	0.52	100.4
	62.9	17.1	8.41	1.02	1.04	4.03	0.29	0.10	0.41	0.24	2.58	0.04	0.02	0.47	0.08	0.13	0.10	0.06	0.71	0.18	0.50	100.4
Average	**62.7**	**17.0**	**8.53**	**1.02**	**1.05**	**4.08**	**0.30**	**0.10**	**0.41**	**0.25**	**2.61**	**0.05**	**0.01**	**0.49**	**0.09**	**0.15**	**0.10**	**0.05**	**0.74**	**0.17**	**0.51**	**100.5**
Published	*61.6*	*17.0*	*8.56*	*1.00*	*1.03*	*4.36*	*0.31*	*0.09*	*0.46*	*0.25*	*2.66*	*0.04*	*0.03*	*0.50*	*0.10*	*0.19*	*0.09*	*0.02*	*0.82*	*0.16*	*0.45*	*99.7*

	Li_2O	B_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	CoO	NiO	CuO	ZnO	As_2O_3	SnO_2	Sb_2O_3	PbO	Rb_2O	SrO	Y_2O_3	ZrO_2	BaO	CeO_2	ThO_2	UO_2
Corning A	117	1857	7520	63	32	9916	1794	232	11,122	504	34	1570	16,299	710	97	1065	0.95	57	4448	0.35	0.38	0.24
LA-ICPMS Orleans	130	2017	7521	67	31	9787	1768	243	12,192	560	35	1616	16,329	745	102	997	0.72	51	4254	0.33	0.33	0.24
August 2012	118	1923	7744	64	31	10,584	1827	238	11,025	541	33	1658	17,132	700	93	1114	0.84	57	4686	0.32	0.36	0.23
	123	1994	7626	68	32	9817	1724	238	11,065	521	35	1561	17,857	690	96	1050	0.86	55	4315	0.37	0.37	0.24
	124	1912	7670	65	31	10,130	1820	249	11,921	513	32	1699	17,406	717	97	1057	0.84	54	4327	0.33	0.34	0.24
	127	1965	7582	66	35	10,000	1778	241	11,817	505	33	1656	16,586	674	99	1029	0.89	55	4282	0.34	0.32	0.23
Average	**123**	**1945**	**7611**	**65**	**32**	**10,039**	**1785**	**240**	**11,524**	**524**	**34**	**1627**	**16,935**	**706**	**97**	**1052**	**0.85**	**55**	**4386**	**0.34**	**0.35**	**0.23**
Brill (2012)	*110*	*2200*	*7900*	*67*	*29*	*10,000*	*1700*	*200*	*11,700*	*440*	*33*	*1900*	*17,000*	*725*	*93*	*1100*	*0.46*	*55*	*4600*	*0.29*	*0.37*	*0.23*

Table 2

Major and minor oxide composition of 96 Pergamon glasses, obtained by EPMA, sorted by glass groups in broadly chronological order, and reported in wt%. In **bold** are those element concentrations that are diagnostic for specific groups. The column 'Lab' refers to the laboratory where the analyses were done; see text for details. A fuller description of the analysed samples, including drawings, photographs and details on their dating, is provided as Supporting online material, SOM Table 1. Sample Per 026 was analysed using SEM-EDS at UCL Qatar.

I.D.	Lab	Type	Colour	Working	Dating (H.S.)	SiO_2	Na_2O	K_2O	MgO	Al_2O_3	CaO	FeO	TiO_2	Sb_2O_5	MnO	CuO	CoO	P_2O_5	Cl	SO_3
Per 004	Lo	Sb decol	colourless	mould-formed	1st c. AD	71.1	18.0	0.38	0.39	**1.68**	**5.8**	**0.28**	0.05	**0.79**	bdl	bdl	bdl	0.02	1.18	0.28
Per 027	Lo/Or	Sb decol	colourless	free-blown	1st c. AD	69.7	18.9	0.34	0.32	**1.70**	**6.3**	**0.36**	0.05	**0.63**	bdl	bdl	bdl	0.02	1.15	0.32
Per 028	Ox/Ch	Sb decol	light yellow green, nearly colourless	free-blown	uncertain (without known parallels)	71.7	17.2	0.49	0.38	**1.78**	**6.2**	**0.29**	0.08	**0.89**	bdl	bdl	bdl	0.03	1.09	0.28
Per 054	Lo/Or	Sb decol	white	free-blown	2nd/3rd c. AD	72.2	17.8	0.34	0.43	**1.53**	**5.7**	**0.32**	0.07	**0.51**	bdl	bdl	bdl	0.03	0.92	0.28
Per 058	Lo/Or	Sb decol	colourless	free-blown	2nd half 1st c. AD	71.5	18.1	0.40	0.38	**1.63**	**5.3**	**0.32**	0.06	**0.71**	bdl	bdl	bdl	0.02	1.10	0.26
Per 060	Lo/Or	Sb decol	colourless	free-blown	probably Roman Imperial period	70.4	18.9	0.41	0.40	**1.83**	**5.5**	**0.34**	0.05	**0.87**	bdl	bdl	bdl	0.02	1.00	0.31
Per 063	Ox/Ch	Sb decol	light yellow green, nearly colourless	free-blown	late antique/early Byzantine (or earlier?)	71.2	18.0	0.44	0.50	**2.00**	**6.1**	**0.34**	0.08	**0.58**	bdl	bdl	bdl	0.02	1.26	0.25
Per 090	Lo	Sb decol	yellowish olive	free-blown	probably 3rd/4th c. AD (perhaps earlier)	73.1	17.4	0.36	0.33	**1.72**	**5.6**	**0.25**	0.04	**bdl**	bdl	bdl	bdl	0.08	1.07	0.17
Per 055	Lo/Or	Sb decol	yellowish brown	mould-formed	mid-2nd–early 1st c. BC	72.2	16.4	0.62	0.58	**1.87**	**6.6**	**0.33**	0.06	**bdl**	bdl	bdl	bdl	0.11	0.95	0.12
Per 019	Lo/Or	Sb decol	yellowish green	mould-blown	1st c. AD	72.0	17.2	0.39	0.30	**2.07**	**5.9**	0.29	0.04	**bdl**	**0.29**	bdl	bdl	0.13	1.12	0.14
Per 061	Lo	Sb–Mn decol	greenish yellow	free-blown	uncertain	68.0	18.0	0.51	0.68	2.01	5.5	0.74	0.10	**0.61**	**0.96**	bdl	bdl	0.09	1.09	0.32
Per 067	Lo/Or	Sb–Mn decol	yellowish green	free-blown	presumably late Roman Imperial period	70.3	17.4	0.63	0.48	2.14	6.5	0.36	0.05	**0.43**	**0.51**	bdl	bdl	0.08	1.01	0.21
Per 010	Lo/Or	Sb–Mn decol	greenish blue	mould-blown	mid-1st–beginning 2nd c. AD	69.7	16.9	0.84	0.89	2.06	6.8	0.58	0.07	**0.25**	**0.24**	bdl	bdl	0.23	0.98	0.22
Per 089	Lo	Sb–Mn decol	aqua	free-blown	1st/2nd c. AD	69.7	16.5	0.74	0.57	2.54	7.1	0.51	0.09	**0.22**	**0.71**	bdl	bdl	0.09	0.94	0.21
Per 083	Lo/Or	Sb–Mn decol	yellowish green	mould-formed	2nd c. BC	66.9	18.2	0.62	0.66	2.11	8.6	0.32	0.04	**0.15**	**0.82**	bdl	bdl	0.08	0.89	0.35
Per 020	Lo	Sb–Mn decol	aqua	free-blown	mid-1st–2nd c. AD	70.9	15.9	1.11	0.58	2.28	6.9	0.47	0.06	**0.14**	**0.36**	bdl	bdl	0.15	0.93	0.16
Per 069	Lo/Or	Sb–Mn decol	greenish blue	free-blown	presumably early Roman Imperial period	71.2	16.1	0.72	0.52	2.32	7.0	0.40	0.07	**0.11**	**0.30**	bdl	bdl	0.13	1.06	0.12
Per 042	Lo/Or	n/Mn decol	purple	free-blown	1st half 1st c. AD	67.2	17.6	0.54	0.53	2.28	8.0	0.38	0.05	bdl	**1.77**	bdl	bdl	0.13	0.92	0.25
Per 005	Lo	n/Mn decol	yellowish green	free-blown	probably 3rd/4th c. AD	69.0	15.4	0.59	0.61	2.34	8.8	0.40	0.07	bdl	**1.70**	bdl	bdl	0.14	0.93	0.20
Per 079	Lo/Or	n/Mn decol	light yellow green, nearly colourless	free-blown	3rd–4th c. AD	71.3	15.0	0.50	0.49	2.38	7.4	0.36	0.05	bdl	**1.45**	bdl	bdl	0.11	1.05	0.12
Per 001	Lo	n/Mn decol	colourless	free-blown	2nd c. AD or perhaps little later	71.2	14.8	0.51	0.48	2.35	7.5	0.39	0.06	0.04	**1.43**	bdl	bdl	0.13	0.95	0.12
Per 007	Lo/Or	n/Mn decol	aqua	mould-formed	mid-1st c. BC–mid-1st c. AD	67.8	18.2	0.44	0.49	2.32	7.4	0.41	0.04	bdl	**1.08**	bdl	bdl	0.09	1.15	0.27
Per 077	Lo/Or	n/Mn decol	aqua	mould-formed	1st half 1st c. AD	70.8	15.3	0.73	0.52	2.35	7.6	0.36	0.05	bdl	**0.74**	bdl	bdl	0.18	0.98	0.13
Per 002	Lo/Or	n/Mn decol	amber	mould-formed	3rd third 1st c. BC–mid-1st c. AD	70.3	16.5	0.60	0.49	2.39	7.2	0.35	0.04	bdl	**0.58**	bdl	bdl	0.12	1.00	0.15
Per 035	Lo/Or	n/Mn decol	colourless	mould-formed	end 1st c. BC–early 1st c. AD	70.4	15.6	0.51	0.50	2.03	8.6	0.27	0.04	0.05	**0.51**	bdl	bdl	0.08	0.98	0.20
Per 075	Lo/Or	n/Mn decol	greenish blue	free-blown	2nd half 1st–1st half 2nd c. AD	72.3	15.1	0.43	0.44	2.59	7.0	0.28	0.04	bdl	**0.37**	bdl	bdl	0.08	1.13	0.15
Per 049	Lo/Or	n/Mn decol	olive yellow	free-blown	3rd third 1st–1st third 2nd c. AD	70.1	16.8	0.49	0.46	2.34	7.7	0.33	0.04	bdl	**0.35**	bdl	bdl	0.15	1.01	0.14
Per 057	Lo/Or	n/Mn decol	aqua	free-blown	1st c. AD	72.4	15.7	0.39	0.40	2.26	6.9	0.22	0.04	bdl	**0.26**	bdl	bdl	0.10	1.07	0.16
Per 059	Lo/Or	n/Mn decol	greenish blue	free-blown	mid-1st–mid-2nd c. AD	72.3	15.5	0.47	0.42	2.11	7.2	0.27	0.05	bdl	**0.25**	bdl	bdl	0.13	1.03	0.13
Per 082	Lo/Or	n/Mn decol	aqua	free-blown	1st c. AD	69.7	16.8	0.74	0.47	2.38	7.8	0.37	0.04	bdl	**0.24**	bdl	bdl	0.16	0.95	0.21
Per 097	Lo	n/Mn decol	yellowish green	free-blown	2nd half 3rd–1st half 4th c. AD	71.9	15.6	0.52	0.45	2.34	7.3	0.31	0.06	bdl	**0.19**	bdl	bdl	0.15	0.86	0.13
Per 018	Lo	n/Mn decol	yellowish green	free-blown	3rd–4th c. AD	71.4	15.4	0.58	0.53	2.44	7.9	0.34	0.06	bdl	**0.10**	bdl	bdl	0.13	0.82	0.16
Per 084	Lo	n/Mn decol	yellowish olive	free-blown	probably 3rd–4th c. AD	71.8	15.8	0.50	0.41	2.57	7.1	0.29	0.02	bdl	**0.08**	bdl	bdl	0.11	1.03	0.11
Per 044	Lo/Or	n/Mn decol	greenish blue	free-blown	mid-1st c. AD	71.1	16.1	0.45	0.40	2.32	7.8	0.33	0.04	bdl	bdl	bdl	bdl	0.09	1.10	0.14
Per 013	Lo	n/Mn decol	yellowish green	free-blown	mid-1st–2nd c. AD	72.3	15.4	0.37	0.40	2.36	7.6	0.27	0.06	bdl	bdl	bdl	bdl	0.10	1.03	0.11
Per 021	Lo	n/Mn decol	yellow green	free-blown	2nd–beginning 3rd c. AD	71.6	15.9	0.49	0.39	2.37	7.5	0.28	0.04	bdl	bdl	bdl	bdl	0.10	1.07	0.11
Per 045	Lo/Or	n/Mn decol	yellowish brown	mould-formed	3rd–2nd quarter 1st c. BC	69.2	17.2	0.66	0.76	2.37	7.8	0.48	0.05	bdl	bdl	bdl	bdl	0.09	0.89	0.26
Per 098	Lo	n/Mn decol	olive yellow	free-blown	1st half 1st c. AD	71.9	15.5	0.44	0.50	2.29	7.4	0.30	0.04	bdl	bdl	bdl	bdl	0.12	1.15	0.13
Per 022	Lo	n/Mn decol	yellowish green	free-blown	1st–early 2nd c. AD	72.8	15.2	0.48	0.42	2.48	6.9	0.30	0.05	bdl	bdl	bdl	bdl	0.12	0.99	0.08
Per 070	Lo/Or	n/Mn decol	yellowish green	mould-blown	1st c. AD	71.3	16.4	0.55	0.45	2.39	7.1	0.30	0.05	bdl	bdl	bdl	bdl	0.16	1.06	0.14
Per 012	Lo	Co bl	ultramarine	free-blown	1st–3rd quarter 1st c. AD	68.7	17.3	0.56	0.50	2.28	7.8	0.81	0.04	bdl	0.42	0.05	**0.04**	0.08	0.85	0.39
Per 014	Lo/Or	Co bl	cobalt blue	mould-formed	end 2nd–early 1st c. BC	69.2	17.3	0.65	0.57	1.78	6.6	1.28	0.07	0.12	0.45	0.39	**0.29**	0.10	0.82	0.22
Per 023	Lo/Or	Co bl	blue	mould-formed	end 1st c. BC–early 1st c. AD	69.7	16.4	0.53	0.56	2.41	7.6	1.19	0.05	bdl	0.17	0.10	**0.09**	0.10	0.78	0.19
Per 024	Lo/Or	Co bl	pale blue	core-formed	2nd–1st half 1st c. BC	67.4	17.0	0.61	0.57	2.22	8.1	1.33	0.05	bdl	1.07	0.12	**0.04**	0.11	0.85	0.29
Per 026	Qa	Co bl	ultramarine	free-blown	late Hellenistic/early Roman Imperial period	68.5	16.3	0.61	0.60	2.46	8.0	1.39	0.07	0.18	0.36	0.11	**0.10**	0.09	0.82	0.23
Per 050	Lo/Or	Co bl	ultramarine	free-blown	1st half 1st c. AD	68.2	17.5	0.56	0.56	2.26	8.2	0.75	0.04	bdl	0.26	0.06	**0.06**	0.13	0.99	0.27
Per 068	Lo/Or	Co bl	ultramarine	free-blown	1st c. AD	69.2	16.9	0.76	0.52	2.39	7.3	0.83	0.03	bdl	0.55	0.09	**0.07**	0.14	0.75	0.28
Per 073	Lo/Or	Co bl	ultramarine	free-blown	1st half 1st c. AD	68.4	17.7	0.53	0.50	2.36	7.6	0.79	0.05	bdl	0.33	0.07	**0.06**	0.11	1.08	0.25
Per 086	Lo/Or	Co bl	cobalt blue	core-formed	3rd–2nd c. BC	65.0	15.9	0.75	0.62	2.17	8.3	0.76	0.05	0.04	0.51	0.45	**0.07**	0.12	0.82	0.31

(continued on next page)

Table 2 (*continued*)

I.D.	Lab	Type	Colour	Working	Dating (H.S.)	SiO_2	Na_2O	K_2O	MgO	Al_2O_3	CaO	FeO	TiO_2	Sb_2O_5	MnO	CuO	CoO	P_2O_5	Cl	SO_3
Per 033	Ox/Ch	Co bl	ultramarine	free-blown	early Roman Imperial period	69.6	15.1	0.50	0.47	2.35	8.2	0.77	0.05	2.05	0.42	0.10	0.07	0.16	0.96	0.24
Per 064	Ox/Ch	Co bl	greenish blue	cast	early or late Byzantine	67.2	15.0	0.70	0.63	2.55	8.5	0.68	0.01	0.98	0.65	0.37	0.02	0.18	0.89	0.20
Per 066	Ox/Ch	Co bl	greenish blue	free-blown	late antique/early Byzantine	66.3	14.5	0.57	0.62	2.43	8.4	0.99	0.09	1.29	0.53	0.52	0.03	0.16	0.67	0.21
Per 080	Lo/Or	Co bl	cobalt blue		late Roman Imperial or Byzantine	66.8	13.0	1.07	0.63	2.20	9.2	0.92	0.05	3.97	0.30	0.30	0.24	0.18	0.29	0.64
Per 003	Lo	Lev I	colourless	free-blown	mid-1st–2nd c. AD	71.0	13.2	0.37	0.55	3.04	8.7	0.39	0.06	bdl	1.46	bdl	bdl	0.07	1.00	0.07
Per 029	Lo/Or	Lev I	yellowish green	free-blown	mid-3rd c. AD	70.0	14.1	0.53	0.62	3.02	8.1	0.57	0.06	bdl	1.85	bdl	bdl	0.10	0.94	0.09
Per 100	Ox/Ch	Lev I	light olive, nearly colourless	cast	probably late antique	68.7	16.2	0.73	0.57	2.81	9.1	0.35	0.07	bdl	1.15	bdl	bdl	0.09	0.94	0.21
Per 065	Ox/Ch	Lev II	greenish blue	cast	early or late Byzantine	73.5	14.5	0.53	0.44	3.13	7.3	0.49	0.12	bdl	bdl	bdl	bdl	0.05	0.79	0.15
Per 056	Lo/Or	w HIMT	yellowish green	mould-blown	2nd half 1st c. AD	66.3	19.2	0.46	0.96	2.24	6.7	**1.08**	**0.16**	bdl	**1.09**	bdl	bdl	0.07	1.17	0.31
Per 094	Lo	w HIMT	greenish blue	free-blown	5th–7th c. AD	69.3	17.7	0.59	0.78	2.80	5.9	**0.82**	**0.16**	bdl	**0.46**	bdl	bdl	0.11	0.73	0.26
Per 085	Ox/Ch	w HIMT	aqua	free-blown	5th/6th c. AD	66.5	18.0	0.78	0.95	2.50	8.6	**0.85**	**0.16**	bdl	**0.79**	bdl	bdl	0.15	0.84	0.21
Per 099	Ox/Ch	HIMT	greenish olive	cast	probably late antique	65.8	18.6	0.49	0.89	2.53	6.3	**1.20**	**0.47**	bdl	**2.64**	bdl	bdl	0.05	1.00	0.28
Per 008	Lo/Or	HBAl	black olive	bracelet	12th/13th c. AD	60.9	15.2	1.81	1.43	**10.4**	4.8	1.69	0.59	bdl	bdl	bdl	bdl	0.19	0.95	0.10
Per 009	Ox/Ch	HBAl	yellowish olive	chunk	uncertain (find context 13th c. AD)	53.0	19.5	1.71	2.21	**11.4**	7.4	2.85	0.64	bdl	0.27	bdl	bdl	0.27	1.01	0.13
Per 011	Lo/Or	HBAl	brownish red	bracelet	Roman Imperial or early Byzantine	60.1	13.1	1.63	1.42	**9.5**	5.1	3.99	0.59	bdl	0.66	0.74	bdl	0.23	0.74	0.10
Per 015	Ox/Ch	HBAl	dark yellowish green	free-blown	presumably 12th–beginning 13th c. AD	56.5	17.3	1.77	1.42	**9.7**	5.0	1.60	0.65	bdl	2.95	bdl	bdl	0.36	0.98	0.13
Per 031	Lo/Or	HBAl	black olive	bracelet	13th c. AD	59.1	17.0	1.56	1.45	**10.1**	5.0	1.71	0.63	bdl	bdl	bdl	bdl	0.22	1.14	0.20
Per 038	Lo/Or	HBAl	black olive	bracelet	12th/13th c. AD	58.6	18.9	1.58	1.27	**9.8**	4.3	1.50	0.57	bdl	bdl	bdl	bdl	0.23	1.23	0.26
Per 040	Lo/Or	HBAl	yellowish green	bracelet	Byzantine	72.9	12.0	1.20	0.80	**3.6**	5.9	1.10	0.27	bdl	1.09	bdl	bdl	0.09	0.36	0.06
Per 043	Ox/Ch	HBAl	dark red marbled	free-blown	8th/9th c. AD (early Islamic)	56.7	14.5	2.14	2.24	**11.0**	7.4	2.74	0.72	bdl	bdl	0.67	bdl	0.28	0.99	0.16
Per 046	Lo/Or	HBAl	yellowish green	free-blown	early Byzantine	65.7	14.5	1.73	0.83	**8.0**	4.5	1.10	0.35	bdl	0.61	bdl	bdl	0.15	0.53	0.22
Per 047	Ox/Ch	HBAl	brownish green	free-blown	late Byzantine	63.8	18.3	1.21	1.18	**6.7**	4.4	1.41	0.50	bdl	0.63	bdl	bdl	0.27	1.15	0.15
Per 053	Ox/Ch	HBAl	yellowish brown	free-blown	8th–early 9th c. AD (early Islamic)	55.3	17.8	1.78	1.58	**9.9**	5.3	1.95	0.63	bdl	3.66	bdl	bdl	0.36	0.95	0.15
Per 062	Ox/Ch	HBAl	reddish brown	free-blown	12th/13th c. AD (Islamic, probably Mamluk)	57.4	22.3	1.08	1.34	**8.1**	4.8	1.85	0.60	bdl	1.38	bdl	bdl	0.22	1.14	0.31
Per 071	Ox/Ch	HBAl	yellowish olive	free-blown	12th/13th c. AD	57.8	19.2	1.27	1.57	**9.8**	5.3	2.16	0.82	bdl	0.59	bdl	bdl	0.24	1.14	0.06
Per 072	Lo/Or	HBAl	dark olive green	free-blown	4th/5th c. AD	57.1	19.1	1.50	1.36	**9.5**	4.4	1.60	0.60	bdl	1.40	bdl	bdl	0.26	1.10	0.12
Per 091	Lo/Or	HBAl	black olive	bracelet	mid- or (most probably) late Byzantine	52.9	24.2	1.23	1.30	**9.7**	4.6	1.79	0.58	bdl	bdl	bdl	bdl	0.39	1.45	0.18
Per 096	Ox/Ch	HBAl	dark red marbled	free-blown	8th/9th c. AD (early Islamic)	57.6	18.5	1.82	1.47	**9.9**	4.7	2.12	0.68	bdl	0.16	1.50	bdl	0.32	1.19	0.16
Per 032	Ox/Ch	HLiBAl	olive green	free-blown	end 12th–beginning 13th c. AD	60.3	15.5	1.62	1.26	**7.4**	8.3	1.09	0.30	bdl	1.43	bdl	bdl	0.10	0.44	0.34
Per 034	Lo/Or	HLiBAl	colourless	free-blown	2nd half 1st c. AD (find context)	72.0	13.4	0.69	0.87	**0.9**	9.4	0.40	0.04	bdl	0.73	bdl	bdl	0.10	0.10	0.59
Per 036	Lo/Or	HLiBAl	yellowish green	free-blown	mid-3rd c. AD (find context)	64.1	15.0	1.63	0.96	**6.2**	8.2	0.68	0.19	bdl	0.56	bdl	bdl	0.10	0.16	0.51
Per 037	Ox/Ch	HLiBAl	light olive green, nearly colourless	free-blown	12th/13th c. AD	67.9	14.5	1.25	0.89	**3.2**	9.4	0.55	0.10	bdl	1.46	bdl	bdl	0.11	0.06	0.51
Per 039	Ox/Ch	HLiBAl	light reddish brown	free-blown	late Byzantine	65.1	14.0	2.06	0.84	**5.9**	9.1	0.64	0.12	bdl	1.28	bdl	bdl	0.10	0.08	0.51
Per 041	Lo/Or	HLiBAl	bluish green	bracelet	Byzantine	68.7	13.2	1.14	1.21	**2.6**	11.1	0.67	0.09	bdl	0.12	bdl	bdl	0.13	0.34	0.19
Per 048	Ox/Ch	HLiBAl	olive green	free-blown	12th/13th c. AD	62.0	15.2	2.22	1.12	**5.9**	10.0	0.90	0.15	bdl	0.72	bdl	bdl	0.14	0.15	0.33
Per 051	Ox/Ch	HLiBAl	green olive	free-blown	13th c. AD	59.7	18.4	1.51	1.23	**5.4**	10.8	0.94	0.21	bdl	0.92	bdl	bdl	0.16	0.40	0.56
Per 076	Lo/Or	HLiBAl	colourless	free-blown	early or mid-Byzantine	65.4	13.3	2.23	0.76	**6.5**	7.9	0.61	0.09	bdl	0.87	bdl	bdl	0.04	0.08	0.46
Per 078	Ox/Ch	HLiBAl	yellowish green	free-blown	12th/13th c. AD	64.0	15.8	1.58	1.02	**5.3**	9.6	0.66	0.11	bdl	0.56	bdl	bdl	0.06	0.08	0.46
Per 081	Ox/Ch	HLiBAl	reddish brown	free-blown	12th/13th c. AD	67.4	14.8	1.00	0.97	**2.4**	10.1	0.71	0.12	bdl	1.37	bdl	bdl	0.10	0.09	0.52
Per 087	Ox/Ch	HLiBAl	reddish brown	cast	mid- or (most probably) late Byzantine	61.5	16.6	1.75	0.99	**5.2**	10.1	0.51	0.12	bdl	1.56	bdl	bdl	0.08	0.07	0.53
Per 016	Ox/Ch	PA	colourless	free-blown	2nd half 13th c. AD (Mamluk)	70.0	10.7	**2.54**	**3.59**	0.9	8.4	0.37	0.22	bdl	0.90	bdl	bdl	**0.25**	0.72	0.28
Per 017	Ox/Ch	PA	olive	free-blown	12th–13th c. AD	70.1	12.0	**2.16**	**3.13**	1.2	8.4	0.57	0.23	bdl	1.00	bdl	bdl	**0.32**	0.81	0.21
Per 025	Ox/Ch	PA	yellowish brown	free-blown	18th c. (Ottoman)	59.6	14.0	**3.27**	**2.31**	7.5	6.8	1.69	0.28	bdl	2.68	bdl	bdl	**0.45**	0.74	0.07
Per 052	Ox/Ch	PA	blue	chunk	uncertain (Byzantine find context)	66.3	14.6	**3.47**	**4.52**	0.7	8.5	0.38	0.03	bdl	bdl	bdl	bdl	**0.29**	0.86	0.23
Per 074	Ox/Ch	PA	olive yellow	free-blown	2nd half 13th c. AD (Mamluk)	69.0	12.0	**1.69**	**2.55**	1.4	10.3	0.97	0.25	bdl	1.60	bdl	bdl	**0.35**	0.90	0.16
Per 088	Ox/Ch	European	brownish olive	free-blown	Ottoman (apparently European import)	58.5	2.1	2.14	2.59	7.4	22.8	2.04	0.33	bdl	bdl	bdl	bdl	0.15	0.22	0.28
Per 093	Ox/Ch	Obsidian	black	chunk	find context late Byzantine	75.1	4.2	5.02	0.12	13.5	0.8	0.92	0.14	bdl	bld	bdl	bdl	bld	0.05	bdl

Table 3
Trace element compositions of 96 Pergamon glasses, obtained by LA-ICPMS, sorted by glass groups in broadly chronological order, and reported in μg/g. In **bold** are those element concentrations that are diagnostic for specific groups. Data is reported to single ppm; for higher concentrations in particular we have to assume an error margin in the order of tens of ppm, or more. 0 ppm indicates values below 0.5 ppm.

I.D.	Lab	Type	Li	B	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Sn	Sb	Pb	Rb	Sr	Y	Zr	Ba	La	Ce	Nd	Th	U
Per 027	Lo/Or	Sb decol	0	142	397	6	8	169	1	2	8	12	112	10	4951	33	4	469	4	40	123	5	10	5	1	1
Per 028	Ox/Ch	Sb decol	3	127	296	6	6	155	1	3	9	13	0	0	3994	16	6	397	5	34	126	5	8	4	0	1
Per 054	Lo/Or	Sb decol	3	157	414	8	6	91	0	1	7	10	13	12	3486	19	4	463	6	46	127	6	11	6	1	1
Per 058	Lo/Or	Sb decol	0	123	379	7	8	150	1	2	17	11	13	13	5237	111	5	413	5	43	136	5	10	6	1	1
Per 060	Lo/Or	Sb decol	4	201	410	6	7	134	0	2	3	15	13	11	5995	11	5	411	5	47	142	6	10	5	1	1
Per 063	Ox/Ch	Sb decol	3	167	315	8	6	150	1	3	8	15	0	0	2567	23	5	344	5	37	124	5	9	5	1	1
Per 055	Lo/Or	Sb decol	1	85	330	8	9	285	1	4	12	12	1	7	9	37	7	326	5	30	156	5	9	5	1	1
Per 019	Lo/Or	Sb decol	1	40	316	10	11	2954	5	7	9	14	2	11	33	4	6	337	5	34	185	5	10	5	1	1
Per 067	Lo/Or	Sb–Mn decol	4	184	453	18	9	3625	4	4	10	17	13	13	2955	20	6	462	7	48	215	7	11	6	1	1
Per 010	Lo/Or	Sb–Mn decol	0	175	508	14	11	2871	4	6	22	22	9	17	2291	91	6	461	5	44	210	6	11	6	1	1
Per 083	Lo/Or	Sb–Mn decol	2	96	273	14	40	7627	6	10	6	16	5	7	2019	78	9	601	7	29	229	6	11	6	1	1
Per 069	Lo/Or	Sb–Mn decol	4	168	455	12	10	2524	5	6	41	14	4	26	968	199	7	462	7	47	208	7	12	7	1	1
Per 042	Lo/Or	n/Mn decol	0	117	334	32	10	16,482	44	21	112	26	3	18	323	96	7	641	6	30	336	6	11	6	1	1
Per 079	Lo/Or	n/Mn decol	3	110	410	55	12	9968	9	9	12	13	4	15	429	17	4	498	8	45	368	7	12	7	1	1
Per 007	Lo/Or	n/Mn decol	0	220	309	21	9	9964	12	12	9	15	2	8	17	7	2	507	5	29	346	5	10	6	1	1
Per 077	Lo/Or	n/Mn decol	0	128	334	18	10	7048	14	15	23	26	2	9	147	238	8	463	5	30	243	6	11	6	1	1
Per 002	Lo/Or	n/Mn decol	0	123	279	13	9	5430	19	12	40	20	2	7	36	21	2	418	4	22	208	5	10	5	1	1
Per 035	Lo/Or	n/Mn decol	0	119	269	10	8	4706	5	7	8	13	3	8	589	426	8	516	6	28	199	6	13	6	1	1
Per 075	Lo/Or	n/Mn decol	3	75	337	13	8	4186	3	7	4	9	3	10	0	0	5	461	7	37	239	7	11	7	1	1
Per 049	Lo/Or	n/Mn decol	3	214	330	11	8	2688	2	6	5	10	2	13	50	56	6	463	7	35	215	6	11	6	1	1
Per 057	Lo/Or	n/Mn decol	0	74	294	9	9	2601	4	5	4	10	2	7	0	0	6	394	5	29	204	5	15	6	1	1
Per 059	Lo/Or	n/Mn decol	0	91	300	14	12	2571	4	4	3	10	2	6	0	1	6	427	6	37	232	6	11	6	1	1
Per 082	Lo/Or	n/Mn decol	0	132	331	8	10	2484	4	5	28	13	2	10	138	17	9	429	6	31	294	6	12	6	1	1
Per 044	Lo/Or	n/Mn decol	0	98	317	5	10	743	2	3	11	8	2	8	46	5	6	402	6	32	229	6	12	6	1	1
Per 045	Lo/Or	n/Mn decol	1	85	399	11	10	459	2	4	6	10	2	8	0	0	11	441	6	31	191	6	11	6	1	1
Per 070	Lo/Or	n/Mn decol	1	132	330	7	10	190	1	3	5	10	2	7	1	0	7	360	5	30	198	5	11	5	1	1
Per 014	Lo/Or	Co bl	4	192	499	14	10	4814	**1949**	65	2763	57	36	177	1143	177	7	440	6	37	173	6	10	6	1	1
Per 023	Lo/Or	Co bl	4	280	342	13	11	2567	**577**	16	626	44	4	15	112	201	7	451	6	35	229	7	11	6	1	1
Per 024	Lo/Or	Co bl	0	203	401	21	12	10,767	**178**	21	556	96	4	11	122	422	8	614	7	39	262	7	12	7	1	1
Per 050	Lo/Or	Co bl	0	138	331	11	11	2903	**444**	15	369	23	3	24	109	24	7	480	6	31	220	6	11	6	1	2
Per 068	Lo/Or	Co bl	0	99	354	15	10	5809	**502**	17	549	26	4	38	113	41	11	517	7	37	260	7	12	7	1	2
Per 073	Lo/Or	Co bl	0	124	310	10	10	3656	**393**	12	558	28	3	29	131	76	6	440	6	29	229	6	11	6	1	1
Per 086	Lo/Or	Co bl	1	147	350	16	10	5111	**478**	51	3584	102	154	5935	447	22,727	9	562	8	35	209	8	11	7	1	1
Per 033	Ox/Ch	Co bl	3	117	206	15	12	2849	**458**	24	1073	32	10	9	**10,581**	6465	7	441	9	40	230	7	12	7	1	1
Per 064	Ox/Ch	Co bl	4	137	307	19	9	4674	**101**	21	3385	100	8	334	**6491**	24,095	8	429	6	35	240	6	11	6	1	1
Per 066	Ox/Ch	Co bl	4	127	331	17	9	3666	**169**	16	4277	93	6	551	**5922**	34,970	7	438	7	42	239	7	11	6	1	1
Per 080	Lo/Or	Co bl	0	187	389	12	9	3371	**1622**	67	2055	52	33	68	**33,983**	141	13	499	7	35	242	7	12	7	1	1
Per 029	Lo/Or	Lev I	3	79	414	33	11	13,671	10	24	16	22	4	7	5	5	6	610	8	34	497	8	12	8	1	1
Per 100	Ox/Ch	Lev I	3	108	199	17	10	8847	5	6	28	13	3	1	1	12	10	446	7	33	432	6	12	6	1	1
Per 065	Ox/Ch	Lev II	5	50	400	10	9	178	2	5	27	8	0	3	45	176	9	329	7	40	210	6	13	6	1	2
Per 056	Lo/Or	w HIMT	0	154	1044	35	19	11,353	12	15	110	23	10	20	331	78	5	702	8	88	614	9	16	9	1	1
Per 085	Ox/Ch	w HIMT	7	149	679	27	15	7116	12	14	89	31	0	18	50	277	9	546	8	65	260	7	13	7	2	2
Per 099	Ox/Ch	HIMT	5	188	1232	50	50	18,016	11	16	146	27	5	12	5	101	5	424	9	173	1236	8	15	8	2	1
Per 008	Lo/Or	HBAl	21	**665**	3983	52	75	283	4	29	14	19	323	10	1	9	46	196	26	284	431	30	60	28	9	4
Per 009	Ox/Ch	HBAl	24	**1424**	3156	78	92	902	9	50	37	38	259	3	1	18	34	188	29	282	537	29	58	26	10	9
Per 011	Lo/Or	HBAl	58	**832**	3936	165	74	8411	27	59	7258	26	498	61	229	724	36	478	29	390	2651	59	101	41	24	4
Per 015	Ox/Ch	HBAl	18	**941**	3123	310	83	20,431	27	40	21	41	227	2	3	14	35	207	29	279	5259	29	59	26	8	7
Per 031	Lo/Or	HBAl	21	**953**	4031	55	78	298	5	32	7	32	225	9	1	6	36	195	27	279	424	32	66	30	9	6
Per 038	Lo/Or	HBAl	20	**1120**	3544	51	66	463	5	28	72	20	447	24	1	16	36	178	23	226	375	27	58	24	8	5
Per 040	Lo/Or	HBAl	126	**1123**	1766	23	60	9651	8	22	32	73	70	14	30	64	23	192	12	134	239	12	21	11	4	1
Per 043	Ox/Ch	HBAl	26	**580**	1965	60	97	516	10	61	5698	40	169	554	41	356	55	230	33	311	369	29	52	25	7	2
Per 046	Lo/Or	HBAl	103	**940**	2216	91	40	6325	13	15	5	25	299	8	7	44	61	850	18	180	1769	23	46	19	11	4
Per 047	Ox/Ch	HBAl	16	**1066**	1264	67	70	4051	9	26	9	22	1451	1	1	12	29	161	22	232	484	20	41	18	5	5

(*continued on next page*)

Table 3 (*continued*)

I.D.	Lab	Type	Li	B	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	As	Sn	Sb	Pb	Rb	Sr	Y	Zr	Ba	La	Ce	Nd	Th	U
Per 053	Ox/Ch	HBAl	23	**954**	2621	57	85	26,383	6	43	31	672	524	7	196	44	36	408	27	266	733	27	54	25	9	5
Per 062	Ox/Ch	HBAl	17	**657**	1909	43	66	8115	5	27	15	44	341	13	578	29	20	193	20	215	249	20	42	19	6	14
Per 071	Ox/Ch	HBAl	24	**712**	3757	82	103	4000	16	34	10	31	140	2	2	19	25	221	35	400	1334	36	74	33	12	6
Per 072	Lo/Or	HBAl	17	**1124**	3810	288	58	11,703	14	29	333	26	604	45	4	28	33	180	29	295	4212	31	64	31	11	4
Per 091	Lo/Or	HBAl	26	**1750**	3889	69	78	294	4	32	10	16	803	11	0	9	24	182	29	311	428	33	59	31	10	6
Per 096	Ox/Ch	HBAl	19	**694**	1952	66	81	1108	8	39	11,218	31	214	115	19	492	47	156	25	237	514	26	54	24	7	3
Per 032	Ox/Ch	HLiBAl	**258**	**1337**	1641	153	44	10,601	21	22	11	34	6	2	15	24	71	1986	22	169	2766	19	41	17	11	8
Per 034	Lo/Or	HLiBAl	**347**	**1195**	285	141	7	6912	9	5	9	15	22	8	10	2	53	3596	2	15	1826	3	8	3	1	1
Per 036	Lo/Or	HLiBAl	**247**	**1223**	1100	68	21	5043	8	7	23	17	67	10	7	12	69	2656	12	89	1360	15	33	13	9	3
Per 037	Ox/Ch	HLiBAl	**303**	**1433**	308	226	9	9996	20	7	15	29	27	1	42	36	75	2895	5	31	2977	8	15	6	5	2
Per 039	Ox/Ch	HLiBAl	**277**	**1367**	366	123	9	9448	14	6	10	31	34	1	10	35	112	2517	11	43	2714	13	57	10	9	4
Per 041	Lo/Or	HLiBAl	**376**	**1181**	552	22	9	1399	2	5	4	14	12	9	11	6	84	5563	3	24	517	7	14	5	3	1
Per 048	Ox/Ch	HLiBAl	**339**	**1451**	363	66	10	5190	13	9	14	26	28	1	8	18	117	2663	9	49	1139	12	27	9	10	4
Per 051	Ox/Ch	HLiBAl	**300**	**1362**	791	82	30	6483	20	12	9	27	242	1	8	18	87	3079	17	129	1973	15	30	13	9	3
Per 076	Lo/Or	HLiBAl	**256**	**1093**	520	112	5	6946	12	4	7	19	23	9	8	16	102	2652	9	33	1749	11	21	8	10	4
Per 078	Ox/Ch	HLiBAl	**352**	**1784**	592	66	6	3836	6	7	8	26	0	1	9	27	97	2644	7	26	1139	10	26	7	12	5
Per 081	Ox/Ch	HLiBAl	**388**	**1810**	587	169	8	9865	16	7	15	24	2	0	14	8	66	3120	5	28	2754	8	15	6	3	1
Per 087	Ox/Ch	HLiBAl	**438**	**1722**	447	172	6	10,766	14	7	8	35	0	7	9	24	112	2979	9	27	2789	8	24	7	9	4
Per 016	Ox/Ch	PA	6	70	1047	20	16	7091	7	9	41	69	0	1	0	39	9	541	7	125	359	6	13	6	1	1
Per 017	Ox/Ch	PA	6	57	1072	18	19	8224	8	9	33	94	0	48	0	149	9	554	7	119	208	6	12	6	1	1
Per 025	Ox/Ch	PA	22	2	1373	30	19	21,094	12	22	55	114	0	15	1	170	39	327	17	129	1095	27	54	20	7	3
Per 052	Ox/Ch	PA	11	93	139	6	3	191	59	5	113	98	0	11	2	232	10	544	2	8	44	2	3	1	0	0
Per 074	Ox/Ch	PA	8	55	809	23	23	11,213	7	14	62	131	2	1	1	22	8	505	10	118	234	7	14	7	1	2
Per 088	Ox/Ch	European	32	51	1705	42	61	519	6	23	14	53	0	3	1	27	64	382	21	182	286	25	48	23	9	3
Per 093	Ox/Ch	Obsidian	63	32	451	3	3	584	0	2	3	39	5	2	1	52	173	90	9	96	390	39	74	18	18	6

the range and diversity of glass used at Pergamon from the mid-4th century BC up to the beginning of the Islamic period in the early 14th century AD. More than forty percent of the samples date to the period up to the 2nd century AD; about a third date to the Late Roman and Early Byzantine periods at Pergamon, roughly speaking from the 3rd to 7th centuries AD, while the remaining circa twenty percent date to the 12th to 14th centuries AD. Only two samples are dated to the 8th/9th century AD when mineral natron glass production is thought to have come to an end (Whitehouse, 2002; Shortland et al., 2006), and none to the 10th and 11th centuries. It has to be stressed that the numbers of samples analysed are not representative of the relative proportions of different glass types excavated at Pergamon. Due to the difficult stratigraphic situation in the excavation areas of Pergamon resulting from the continuous settlement the presumed dates of the samples were established not only in terms of their context and the associated material but also through typological comparison with finds from other sites, sometimes leading to rather broad date ranges (Table SOM 1).

For analysis, small (around 3 mm long) fragments from all samples were mounted in transparent resin blocks, where possible as cross sections, and ground and polished to expose uncorroded glass for electron probe micro analysis (EPMA). Two thirds of the samples were analysed at the Wolfson Archaeological Science Laboratories at the UCL Institute of Archaeology, while the remaining samples were analysed in the Research Laboratory for Archaeology and the History of Art, University of Oxford (Schibille, 2011). Both instruments were calibrated using elemental or simple stoichiometric compounds, and the calibration tested by analysing Corning glasses A and B alongside the unknown samples (Table 1 for the UCL EPMA). The analyses are in close agreement within a few percent relative of the published values (Brill, 1999; Vicenzi et al., 2002); the Oxford data are as reported in Schibille (2011).

About three quarter of the assemblage was further analysed for their trace element content by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS), partly in collaboration with Dr Bernard Gratuze at the IRAMAT laboratory in Orleans (UCL samples, labelled Lo/Or in Tables 2 and 3), and partly by Dr Laure Dussubieux at the Field Museum in Chicago (Oxford samples, labelled Ox/Ch in Tables 2 and 3; Schibille, 2011). A comparison of trace element concentrations for Corning A (Brill, 2012) and measured values from the laboratory in Orleans is given in Table 1. While no direct comparison of the performance of the two LA-ICPMS laboratories was done for these samples, there is no systematic difference visible for data from similar glasses analysed in the different labs; the data is assumed to be fully compatible.

We first used a visual assessment of the concentration of diagnostic minor oxides (Al_2O_3, CaO, TiO_2, MnO and Sb_2O_5) to allocate the analysed samples to specific major glass compositional groups. The initial allocation was then checked by comparing the remaining minor oxides in the newly-analysed samples with values typically found in the published glass groups to obtain a subjective best fit. With very few exceptions, these allocations are unambiguous. However, it is important to remember that none of these groups have formally defined compositional ranges, and different authors not only use different names for similar, even identical groups, but there are also subtle differences in composition within groups. We also stress that even the diagnostic oxides are not always suitable for a strict definition of compositional 'space' to which a sample must adhere in order to be recognized as a member of that group. This is probably best illustrated by the case of the antimony-decoloured group including three samples with no antimony oxide detectable by electron microprobe analysis, and a more yellowish tint (Per 019, 055 and 090; Table 2). However, since all other diagnostic oxides match with this group, but not the others, we assigned them to this group regardless. They were probably produced from the same sand as the antimony-decoloured glass, but for some reason had no antimony added to them.

For this paper, we refer predominantly to published data from Jackson and co-workers (Jackson, 2005; Foster and Jackson, 2009, 2010), Paynter (2006) and Gallo et al. (2013) for Roman blue/green and colourless glass; Silvestri et al. (2008) for antimony- and manganese-decoloured glass; and Mirti et al. (1993), Freestone (2005, 2006; Freestone et al., 2002a,b), Foy and co-workers (Foy et al., 2003), Foster and Jackson (2009, 2010) and Rehren et al. (2010) for Levantine and HIMT glass.

3. Results

The results of our analyses are reported in Table 2 (oxides) and 3 (trace elements); a catalogue of samples is provided in the Supplementary online material. The archaeological context indicated prosperity during the Hellenistic and Roman era, followed by a less active period in the mid-1st millennium AD, a hiatus between AD 716 and the 10th century, and resurgence in the early second millennium. The presentation of the data is following these broad periods.

3.1. Early glasses: the Roman tradition

More than half of the samples (52) can be linked to glass compositions known as antimony-decoloured, Roman blue/green, and manganese-decoloured, including all samples from the 2nd century BC to the 2nd century AD. Of these groups, the ten antimony-decoloured glasses show the most consistent compositional pattern (Table 2), in line with data from the *Iulia Felix* ship wreck (Silvestri et al., 2008) for such glass, and similar to Romano-British antimony-decoloured glass (Foster and Jackson, 2010), even though three of them (Per 019, 055 and 090) have no antimony above the detection limit of the EPMA. Four of the ten glass sherds stem from the 1st century AD, including both Roman mould-formed and blown vessels, while a few other examples belong probably to the later Roman Imperial period. Among the antimony-decoloured objects of the early Roman Imperial period are fragments of a colourless mould-formed bowl (Per 004), a mould-blown lotus-beaker (Per 019, Fig. 2a) and a colourless free-blown beaker with facet-cut decoration (Per 058). The beaded stem of a goblet going back to the 4th to 6th centuries AD belongs to the latest pieces (Per 063). The earliest piece (Per 055, a Hellenistic mould-formed grooved bowl) dates to the mid-2nd to early 1st century BC and has good compositional similarity with this group, but has slightly higher lime and potash, somewhat lower soda, and no antimony; its relationship to the antimony-decoloured glass is therefore somewhat tentative.

The largest compositional group, totalling 23 samples, matches the Roman blue/green and Rb/g manganese-decoloured group. The typical Roman pale blue to blue-green ('aqua') glass has been described *inter alia* by Silvestri (2008) and Gallo et al. (2013), and the manganese-decoloured glass from the same ship wreck by Silvestri et al. (2008), where it forms a very tight compositional group. In contrast, the manganese-decoloured glass among the Pergamon samples is much more variable in its manganese content and other minor oxides. Significantly, there appears to be a seamless transition into the Roman blue/green glass, which is differentiated from the manganese-decoloured glass primarily by a lower, or no, manganese content. The manganese-decoloured glass reported in Silvestri et al. (2008) has consistently more than 1 wt% manganese oxide; among the Pergamon samples, the manganese content varies from as high as 1.8 wt% MnO, decreasing almost continuously down to the detection limit (assumed for our analyses by EPMA as 0.01 wt%). We interpret this as a sign of recycling and mixing of normal Rb/g glass with manganese-decoloured glass. Apart from the manganese content there is no significant compositional difference within this group.

These glasses also comprise both mould-formed and free-blown vessels. The mould-formed vessels include ribbed bowls from the late Hellenistic and early Imperial Roman periods (Per 045 [Fig. 2b], Per 002, 007, 077) and a network glass (Per 035) presumably imported from Italy around the turn of the ages (von Saldern, 2004, 181f). The time range of the blown glass goes from the 1st to the 4th century AD. The fragment of an early Roman inscribed beaker of probably Syrian or Cypriote provenance (von Saldern, 2004, 252f) is of special interest (Per 070). It formerly displayed the dictum "ΛΑΒΕ ΤΗΝ ΝΙΚΗΝ – Gain the victory".

Another 13 closely related samples are coloured blue by cobalt and copper oxide (see Table 3). The minor oxide concentrations of nine of these are indistinguishable from the uncoloured Rb/g and manganese-decoloured glasses. However, their levels of transition metal oxides differ substantially. All of them have significantly increased levels of iron oxide, on average more than 0.9 wt% compared to the 0.3 wt% on average found in the Rb/g and manganese-decoloured glasses, as well as consistently around half of one percent manganese oxide. They include Hellenistic core-formed (alabastra Per 024, 086 [Fig. 2c]) and mould-formed vessels (mosaic glass bowl Per 014) as well as mould-formed vessels (mosaic glass bowl Per 023), ribbed cups (so-called Zarte Rippenschalen, Per 012, 050) and free-blown beakers (Per 068, 073) of the early Roman Imperial period.

The combination of copper and cobalt is reminiscent of the Egyptian Late Bronze Age cobalt-blue glass coloured using a preparation derived from cobaltiferous alums (Kaszmarczyk, 1986; Rehren, 2001; Tite and Shortland, 2003; Smirniou and Rehren, 2013), even though it does not have the high alumina, nickel and zinc contents typical of those earlier cobalt-blue glasses. A compositionally very similar glass sample, also of an early date (50 BC to AD 130) was recently published from Bubastis in northern Egypt (Rosenow and Rehren, 2014: Mn 06, a mould-cast ribbed bowl), suggesting a wider use of this colourant across the Eastern Mediterranean.

The remaining four cobalt-blue samples (Per 033, 064, 066 and 080) have more than one percent of antimony oxide, and the first three of these have also similarly elevated levels of lead oxide. Three also have higher copper (Per 064, 066 and 080), overall suggesting a different colourant source for these. Compared to the other cobalt-blue glasses, these have higher lime and lower soda concentrations, making them more similar to Levantine I glasses; their alumina and barium levels, however, are still more in line with the Rb/g glass set. They also are later than the other group (Tables 2 and 3), further underlining their difference from the earlier eight cobalt-coloured glasses.

Seven samples contain antimony oxide at between 0.1 and 0.6 wt% as well as between 0.2 and 1 wt% manganese oxide, labelled Sb–Mn decol in Tables 2 and 3 (Per 010, 020, 061, 067, 069, 083 and 089). Their minor oxide content falls between the antimony-decoloured and the Rb/g manganese decoloured glass groups, suggesting that they represent glass obtained from mixing cullet during recycling of decoloured glass. In the majority the samples are from Roman vessels, for example a mould-blown bottle with a base moulding in shape of a rosette (Per 010, Fig. 2d). An exception is a mould-formed grooved bowl from the 2nd century BC (Per 083).

All three glass groups discussed so far, the antimony-decoloured, the Roman blue/green (with or without manganese) and the mixed glass, have the same general chronological setting in the last few centuries BC and up to about the fourth century AD, and were used for the same range of glass objects. It appears that they

Fig. 2. a: Mould-blown lotus-beaker, nominally antimony-decoloured glass but with a yellowish-green tint and no added antimony; see text for discussion. Sample Per 019 (diam. body 4.5–5 cm). b: Mould-formed late Hellenistic ribbed bowl, Roman b/g glass. Sample Per 045 (diam. rim 18 cm). c: Hellenistic alabastron, Co-blue glass. Sample Per 086 (diam. body 1.5–2.3 cm). d: Mould-blown bottle base with a rosette. Mixed Sb and Mn decol. glass. Sample Per 010 (diam. base 7 cm). e: Early Imperial mould-blown ribbed bowl, weak HIMT glass. Sample Per 056 (diam. rim 7.6 cm). f: 12th century Islamic import, plant ash glass. Sample Per 062 (diam. rim 10.8 cm; diam. base 4.4 cm). g: Snake-trailed lamp, 3rd c AD, HLiBAl glass. Sample Per 036 (max. length 5.2 cm). h: Mamluk enamel-painted beaker, import, plant ash glass. Sample Per 016 (4.4 × 2.7 cm [left]; 1.8 × 2.2 cm [right]).

co-existed side-by-side, rather than one following the other. The presence of several pieces that were most likely imported as finished objects (such as the network glass Per 035 from Italy, the inscribed bowl Per 070 from Syria or Cyprus, and most likely also the delicate ribbed bowls Per 012 and 050), but do not stand out compositionally, is particularly noteworthy.

3.2. *Mid-1st millennium AD: Levantine and HIMT glass*

The glass compositions which during this period dominate elsewhere in the Eastern Mediterranean world are only represented here by eight samples. Three samples were identified as Levantine I (Per 003, 029 and 100), based on their higher alumina and lime content compared to the previous samples. A single sample each was identified as Levantine II (Per 065), based on its even higher alumina and slightly lower lime content compared to the Levantine I samples, and as HIMT glass (Per 099), based on the high titania and iron oxide content. Both are late antique/early Byzantine window panes. The other analysed window panes are Levantine I glass (Per 100), Co-blue glass (Per 064) and HLiBAl glass (see below, Per 087). Three samples (Per 056 [Fig. 2e], an early Roman Imperial mould-blown ribbed bowl, Per 085, a goblet, and Per 094, a *polycandelon*-lamp, the latter both from the early Byzantine period) have slightly elevated levels of titania and iron oxide, in line with the HIMT 2 group defined by Foster and Jackson (2009) for Britain, or the weak HIMT from northern Egypt (Rosenow and Rehren, 2014). Six of these eight Levantine and HIMT samples date to the mid-1st millennium AD, the remaining two date as early as the 1st and 2nd century AD, based on their archaeological context and on typological comparisons (Per 003 Lev I and Per 056 weak HIMT).

3.3. *High boron high alumina glass of the mid-1st to early 2nd millennium*

Almost all archaeological glass analysed so far from Europe and the Near East has less than 250 ppm B and less than 3–4 wt% Al_2O_3. The occurrence at Pergamon of glass with much higher boron and alumina is therefore noteworthy, as first reported by Schibille (2011). We define high-boron glasses as having in excess of 500 ppm B. Nearly one third of all analysed samples (28 out of 97) from Pergamon, and the large majority of glasses dating later than the 5th century AD, belong to this new glass type. There are two sub-types of this group, one with about 1000 ppm B and 9 wt% Al_2O_3 on average, and the other with nearly 1500 ppm B, around 300 ppm Li and around 5 wt% Al_2O_3 (Figs. 3 and 4). We suggest labelling the first of the two sub-groups as HBAl, for High Boron and Alumina, in parallel to the HIMT label, and the second sub-group as HLiBAl, for High Lithium Boron and Alumina.

There are other differences between the two sub-groups, with lime, sulphate, rubidium and strontium all being much higher in HLiBAl glass, and soda, iron oxide, titania, phosphate and arsenic higher in HBAl glass (Tables 2 and 3; Figs. 5 and 6). Remarkable is the very low concentration of chlorine in the HLiBAl glasses, reaching only a fraction of the usual levels of around 1 wt% in other ancient glass, and pointing to an unusually chlorine-poor natron source. Schibille (2011) has developed the argument why this boron-rich glass is likely based on an evaporate deposit related to the major borate deposits in western Asia Minor (grey shaded area in Fig. 1), a few hundred kilometres northeast from Pergamon, but utilising two different sand sources and possibly also two different evaporate deposits. Our data here further corroborates this distinction.

The two types are broadly equally represented among the total Pergamon data set, with 16 HBAl and 12 HLiBAl samples, respectively. HBAl glass often appears almost opaque due to the very dark colour of the glass and relatively thick working. The HBAl group includes vessels from the early Byzantine (Per 046, a lamp with loop-like handles, and Per 072, a mould-blown spiral-ribbed beaker) to the late Byzantine times (Per 047, a bowl, and Per 071, a lamp). There are also several bracelets with and without decoration (Per 008, 011, 031, 038, 040, 091) that predominantly occur in the HBAl-group. Islamic vessel imports of the 8th/9th (Per 043, 053 [?], 096) and 12th/13th century (Per 062 [Fig. 2f]) are noteworthy.

HLiBAl glass is typically transparent and faintly coloured to dark green glass, similar in appearance to HIMT glass. It contains in particular locally produced beakers of the 12th/13th century decorated with applied threads and prunts (Per 037, 048, 051, 078, 081), but also a vessel sherd with enamel-painted decoration, a product most likely from a Mamluk glass factory (Per 032). Furthermore one bracelet (Per 041), a spindle whorl (Per 080) and a crown glass window pane (Per 087) belong to this group. A beaker of the 2nd half of the 1st century AD (Per 034) and a snake-trailed lamp of the mid-3rd century AD (Per 036, Fig. 2g) have to be considered as extraordinary early in date, however their find contexts are well dated.

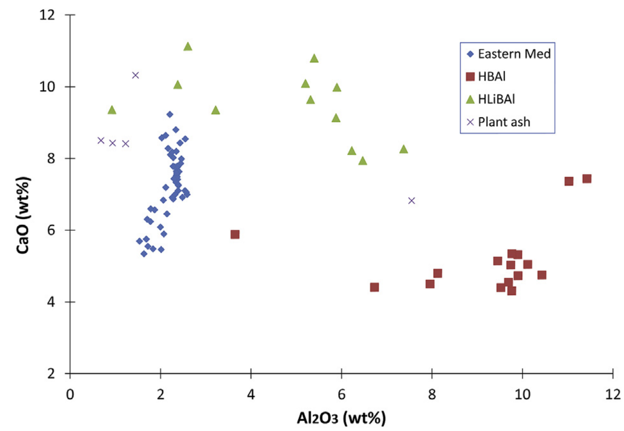

Fig. 4. CaO vs Al_2O_3 in all Pergamon glasses – note the clear separation of the early glasses from the two new glass groups.

3.4. *Other glasses*

Four glasses from the 12th to 13th century are typical plant ash glasses (Per 016, 017, 052, 074). They include two enamel-painted beakers imported from the Mamluk realm and dating to the 2nd

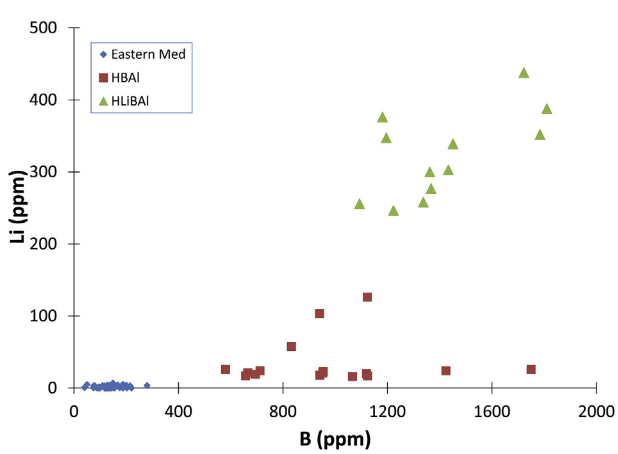

Fig. 3. Li vs B in all Pergamon glasses. 'Eastern Med' captures all glasses in this assemblage that have been assigned to one of the established 1st millennium AD eastern Mediterranean compositional groups, including the various decoloured and cobalt-coloured glasses, Levantine I/II and the HIMT/weak HIMT glasses.

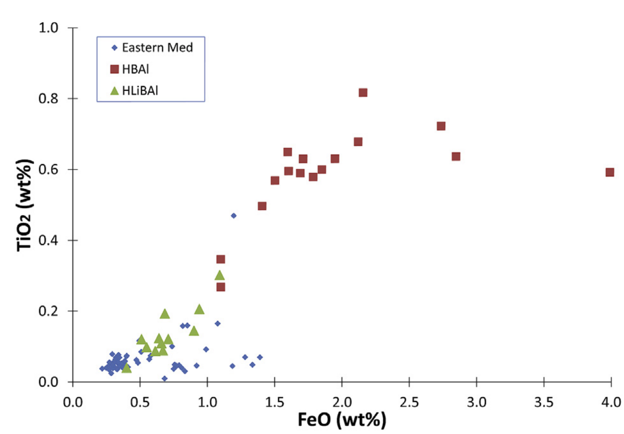

Fig. 5. TiO_2 vs FeO in Pergamon glass. The HBAl group has much higher values in both oxides than the other glasses. Note also the elevated iron oxide values in the cobalt-coloured early glasses.

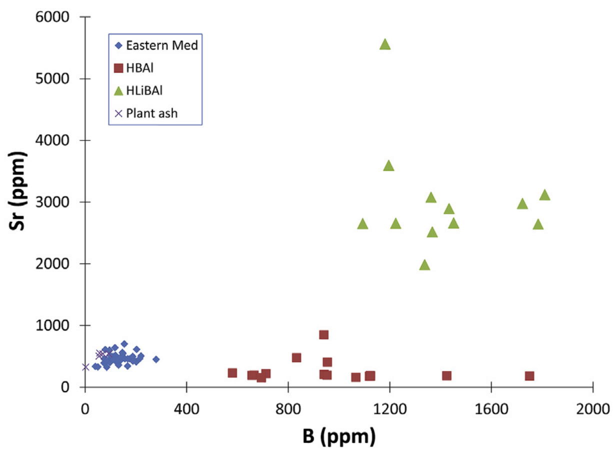

Fig. 6. Sr vs B in Pergamon glass. Note the extremely high Sr content of the Li-rich glass.

half of the 13th century (Per 016 [Fig. 2h], Per 074). A fifth plant ash glass is an Ottoman tulip vase of the 18th century (Per 025). Another sample from the later Ottoman period (Per 088) is very unusual and apparently a European import, containing only two percent by weight soda and potash each, but nearly 7.5 wt% alumina and nearly 23 wt% lime. This composition resembles European window glass of the 17th century, which has very similar levels of soda, potash, lime and magnesia, but only about half the alumina and iron oxide levels of this glass (Dungworth, 2012; Scott et al., 2012).

Five suspected chunks of raw glass were analysed; of these, two can be allocated to plant ash glass (Per 052) and HBAl-group (Per 009), respectively. One sample (Per 092) was identified as pure quartz, probably rock crystal, another as obsidian, a black natural glass (Per 093). Both materials were worked in antiquity into artefacts also produced in glass, such as small vessels, beads and other jewellery. Indeed, glass is often seen as a substitute for the rarer and more difficult to work natural precious stones, and the inclusion of such natural materials in an archaeological glass assemblage is not surprising. The last of these (Per 030) is a piece of fully vitrified ceramic and not related to glass working.

4. Discussion

The chemical analysis of the glass samples from Pergamon revealed a similarly complex pattern of different types and groups as was already apparent from the typological study (Schwarzer, 2009; Schwarzer and Rehren, 2015; Schwarzer, in preparation), consistent with the changing fortunes of the city over more than one and a half millennium. They also throw light on several issues of much wider significance, such as the relationship between glass composition and glass working, the primary production of natron glass outside Egypt and the Levant, and the resurgence of plant ash glass making in the early Islamic period.

4.1. Cast vs blown glass

The early glasses in the Pergamon assemblage span the transition from cast glass to blown glass around the first centuries BC and AD. In a previous paper Fischer and McCray (1999) suggested that this change in working technology led to a change in base composition of the glass, from 19 wt% soda to 14 to 15 wt% soda, thought to adjust the viscosity of the glass to suit the new working technology. We therefore compared the average compositions of cast glass with blown glass from the first few centuries AD. There is no noticeable difference between the cast and blown glass compositions respectively, suggesting that at least in the workshops which supplied glass artefacts to Pergamon the change in technology did not trigger a change in glass composition. Fig. 7 illustrates this for the ratio of lime vs soda; the cast and blown glasses overlap almost perfectly, regardless of whether they are decoloured by antimony or manganese, or not decoloured.

4.2. High boron high alumina glass

Dussubieux et al. (2010) recently revisited the complex pattern of ancient high-alumina glasses and identified several distinct groups. One of them is of particular interest for us, as it is closely related to our own analyses, established by several samples from Sardis (Brill, 1968, 1999).[2] Schibille (2011) has built on this, using a sub-set of the current Pergamon samples, and linked this high-alumina glass group to a most likely western Asia Minor production origin related to the borate deposits in western Turkey (see Fig. 1).

Since then, Swan (2012: 193) has reported analyses of 16 medieval bracelets from Hisn al-Tinat in southern Turkey, which include eleven samples with high boron levels similar to the Pergamon glasses. Five of these are similar to our HLiBAl group, while six samples are intensely coloured and characterised by very high alumina and low lime contents, similar to HBAl glass. However, the match between the two pairs of chemical groups is not perfect, with systematic differences in Rare Earth Element concentrations and some minor oxides.

An even higher boron level has been found in seven mid-1st millennium AD glasses from Aphrodisias, southeast of Izmir in western Turkey (Brill, 1968, 1999). These, however, do not have elevated alumina levels. Lauwers et al. (2010) report a bracelet of similar composition from Sagalassos, also in Asia Minor, and Borisov (1989: 292, Table 24) mentions two out of four bracelet analyses with high boron content (0.13wt%), but no elevated alumina; these date to the 11th and 12th century AD from Djadovo in Bulgaria. This scarcity of comparative data is most likely due to the paucity of boron analyses in the literature; the main analytical methods used in glass analyses, such as SEM–EDS, EPMA and XRF, cannot easily detect boron at the low levels typically present.

Taken together, the western Asian high-boron glasses form a complex family of compositional sub-groups, within the overarching group of mineral natron glasses. At present, it is not clear whether the elevated boron levels are introduced with the sand or the natron. However, based on the geographical distribution of these high-boron glass finds, it is highly likely that at least one of the two raw materials would have come from the vicinity of the borate deposits in western Asia Minor. This then suggests that the primary production of these glasses took place somewhere in this region, and not in the known traditional glassmaking regions of Syro-Palestine and Egypt. Significantly, the emergence of this regional glassmaking tradition is not linked to the end of mineral-natron based glass making seen in the south-eastern Mediterranean in the 8th or 9th century AD. The earliest examples of these locally produced high-boron glasses date to the 1st century AD (Per 034) and the 3rd century AD (Per 036), with several others dated to the middle of the 1st millennium AD (Per 046 'early Byzantine', Per 072 '4th to 5th century AD'), and they dominate the Pergamon assemblage from the 6th century AD onwards. Clearly, primary

[2] Brill (1999) reports six high-alumina glasses in his tables; four of these are rich in boron (0.1–0.25 wt% B_2O_3). Two are flat transparent glass, two are black bracelets. The other two are labelled 'slag' in the catalogue, and have low boron (0.01 wt%).

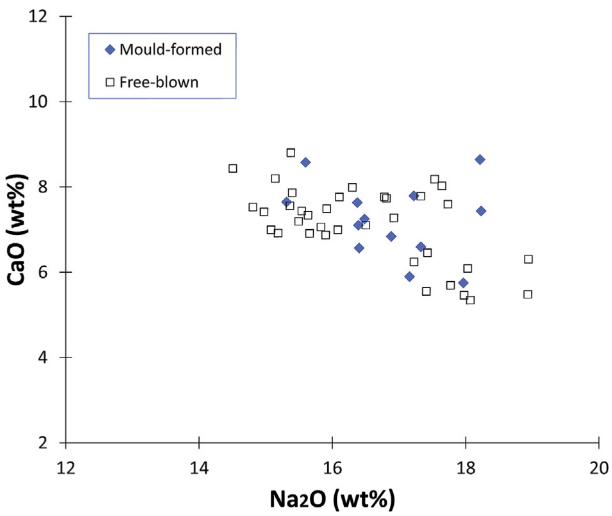

Fig. 7. CaO vs Na_2O values for all early glasses from Pergamon, spanning the transition from cast to blown glass around the first centuries BC and AD. The cast and mould-formed glasses (diamonds) display no different composition than the free- and mould-blown glasses (open squares).

glass production in western Asia Minor coexisted for about half a millennium with the Levantine and Egyptian glassmaking centres, and persisted well into the 2nd millennium AD. The continuing, even increasing dominance of this glass group during the early 2nd millennium, when the supply of mineral natron from the Wadi Natrun had supposedly long come to an end (Whitehouse, 2002), is further strong indication for a local or regional natron source for these glasses. We therefore argue that both the sand and the natron used for these glasses were from the region.

The compositional variability within this broad glass group covers elements which are clearly linked to specific sand sources, such as iron, titanium, and zircon, as well as elements which are most likely entering the glass with the natron source, such as lithium, chlorine and sulphur. The existence of discrete compositional groups suggests that there were a number of different glassmaking sites, using their specific unique sand and individual natron sources rather than relying on a single natron source that was shared more widely.

4.3. The end of mineral natron glass in Pergamon

Relatively few samples date to the late mid-1st millennium AD; about half of them are either Levantine or HIMT glass, while the other half is of the new regional composition rich in boron and alumina. Hardly any glass is known from the late first millennium, after the sack of the city by the Umayyads in 716 AD and the resulting hiatus in settlement. The period which in the Levant saw the switch from mineral natron to plant ash glass is therefore not represented among the Pergamon assemblage.

Only from the 10th and especially in the 12th century AD do we see a resurgence of building activity, and accordingly new deposition of glass in the archaeological record. Interestingly, all of this post-Umayyad glass is of the regional high-alumina composition, with just a few (and often imported) plant-ash based pieces among the analysed samples. Thus, the picture here differs considerably from the re-emergence of plant ash glass as the dominant glass type after the 8th or 9th century AD in the Levant. Significantly, the transition to a new glass recipe does not seem to be linked to the events in the 8th or 9th century in the Nile Delta which have been implicated in the disappearance of mineral natron glass making (Whitehouse, 2002; Shortland et al., 2006). In Pergamon, the new glass composition emerges already several hundred years earlier, at a time when HIMT, Levantine I and II glass was still being produced in large quantities and available even in remote areas such as northern Bulgaria (Rehren and Cholakova, 2010, 2014) or northern England (Freestone and Hughes, 2006). This change in glass consumption is therefore not driven by a lack of production of glass in the Levant, but more likely by changes in the regional connectivity across the Eastern Mediterranean and the regionalisation of the Byzantine economy more generally.

4.4. Regional economy and glass supply

Chunks of raw glass, vitreous slag, manufacturing waste and deformed glass objects suggest local glass working in Pergamon and can be linked to more common vessel types, while rare vessel types within the Pergamenian assemblages are likely imported glass. Glass vessels were extremely rare in Pergamon prior to the 1st century BC (Schwarzer and Rehren, 2015). The results of the sondages in the foundation of the Great Altar, erected shortly before the middle of the 2nd century BC, found thousands of pottery sherds but not a single piece of glass (de Luca and Radt, 1999). Among the earliest glass vessels in Pergamon are a fragment of a mould-formed bowl with leaf decoration and a few pieces of core-formed *amphoriskoi* and *alabastra* from the 4th century BC. All of these are imports. The demand for glass rose with the integration of Pergamon into the Roman Empire, as seen in the increase of mould-formed vessels (grooved bowls, ribbed bowls) during the late 2nd and the entire 1st century BC. They were probably made locally, as indicated by the relatively high number of sherds excavated. The production of ribbed bowls in Pergamon continued until the end of the 1st century AD.

Glassblowing was introduced in Pergamon most likely not before the mid-1st century AD. Fragments of mould-blown vessels of presumably Syrian or Cypriot provenance (von Saldern, 2004, 252f) (Per 070) and a small number of luxurious vessels of the early Imperial period, including mould-formed mosaic glass (Per 023), network glass (Per 035) (von Saldern, 2004, 181f) and vessels with cut decoration (Per 058) presumably imported from Italy around the turn of the ages, suggest extensive trade connections. Their composition does not differ from the locally worked glass, suggesting that glass workshops in Italy and Pergamon used glass made at the same primary factories. Glass working continued throughout the Roman Imperial period but was restricted to utilitarian glass in a broad repertoire of forms. All analysed glasses from these early periods match known compositional groups used extensively elsewhere, confirming the model of centralised glass production, long-distant trade of raw glass, and local glass working, with some import of luxury objects produced elsewhere, but from glass of the same composition.

The transition into the late antique and early Byzantine period followed on seamlessly although the scope of forms was reduced significantly (Schwarzer, 2009). Imports are now rare, probably as a result of the regionalisation of the early Byzantine economy visible elsewhere (Keller, 2006; Hodges, 2012). In Pergamon, this is reflected in the emergence of the regional glass groups rich in boron and alumina (HBAl and HLiBAl), and a paucity of glass groups that are much more dominant elsewhere in the Levant, such as Levantine I and HIMT. Interestingly, glass windows appear to be made predominantly from these imported compositions even though some of the regional glass is as transparent as HIMT; whether they were imported as ready panes, or manufactured locally, remains open.

The interruption of the settlement in Pergamon caused by the conquest of the Umayyads is reflected in a low number of glass finds from the early 8th to 10th centuries AD. With the resettlement of the citadel hill in the middle and late Byzantine period glass workshops were established again in Pergamon, now working almost exclusively the regionally produced glass. During the 12th and 13th centuries locally made beakers with nubbed decoration dominate. These vessels are so far without parallels in Asia Minor but known from the Mamluk realm and from Frankish sites in Europe. Thus, the inhabitants of late Byzantine Pergamon seem to have had contacts to the Mamluk realm, otherwise one cannot explain the remarkable number of Mamluk glass imports uncovered in the excavations on the citadel hill. The large amount of glass bracelets (ca. 1000) is also remarkable, representing almost five percent of all glass finds of the Stadtgrabung (ca. 20,000). This phenomenon is already known on other sites in Asia Minor (Lauwers et al., 2010). The Byzantine glass production ceased with the Seljuk conquest of Pergamon at the beginning of the 14th century.

5. Conclusion

The nature of the glass assemblage from Pergamon, and the changes it underwent over time initially reflect the broad chronological trends known from previous analytical studies of 1st millennium AD glass, from Roman Britain through Italy, Egypt and the Levant. The early phase is dominated by Roman blue/green glass with various levels of manganese decolouration, and by glass decolourised by antimony. The assemblage includes high-quality imported objects as well as locally-produced ones, and no distinction can be made between the main glass groups with regard to their use for particular objects. The import of finished objects as well as raw glass chunks reflect Pergamon's strong position as a major cultural centre, while the similarity of the glass compositions found in Pergamon to those used elsewhere in the Roman world is in line with the prevailing model of a centralised primary glass production supplying raw glass to secondary workshops elsewhere. Glassworkers in Italy and Syria worked glass from the same primary production centres as their colleagues in Pergamon. The introduction of glass blowing, visible in Pergamon from the first century AD, does not affect the composition of the glass used. The recipes for both antimony-decoloured and for Roman blue/green to manganese-decoloured glass remain constant from the Hellenistic period to the end of the Roman period.

The mid-1st millennium AD then sees a decline in the city's fortunes and only limited use of Levantine I and HIMT glass, but also the emergence of new glass groups, rich in boron and alumina. The identification of regionally made glass from the early to mid-1st millennium AD onward is of major importance, as it is the first evidence for regular glass making outside Egypt and the Levant in this period. On geological grounds it is reasonable to assume that this glass was made in the wider region east of Pergamon and north of Sardis, near the borate deposits in western Asia Minor (see Fig. 1). By the time that Pergamon is re-settled in the mid-to late Byzantine period this glass dominates the assemblage, with only a handful of plant ash glasses among the analysed fragments, many of which were imported as finished objects. The regionally produced high-boron glass falls into several chemically distinct sub-groups, indicating the existence of several discrete production sites. Its use is not restricted to Pergamon, since it seems to also have been found as far as Bulgaria and in Hisn al-Tinat in southeast Turkey near the Syrian border. It is probably only due to the limited number of analysed glass assemblages from Asia Minor that this group is not more widely visible. Its introduction had earlier been tentatively linked to the assumed collapse of natron supply during the 8th century AD. However, our wider data set now shows that it already appears in some quantity well before this collapse. Instead, it seems more likely that the emergence of the boron-rich glass groups is due to the availability of boron-rich mineral natron in western Asia Minor and the broader political and economic pattern within the Byzantine Empire at the time, resulting in a more regionalised economy and a reduction in international trade.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.12.025.

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