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Chemical characterisation of archaeological glasses from the Hellenistic site of Jebel Khalid, Syria by electron probe microanalysis

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Abstract

Background: Jebel Khalid is a single period Hellenistic site on the west bank of the Euphrates River in northern Syria. The occupation of the site dates from the early 3rd century BCE until its abandonment in the late 70s BCE. The so-called Governor's Palace, an administrative centre on the Acropolis of the site, overlooked this walled Greek garrison city. A considerable quantity of glass, predominantly drinking bowls, was excavated from this building complex. This study concerns the elemental analysis of glass samples from this assemblage by electron probe microanalysis (SEM-WDS).

Results: The preliminary analyses presented in this report reveal that the Jebel Khalid glasses are of the silica-soda-lime type fluxed with mineral soda, typical of late 1st millennium BCE glass composition. Manganese was employed as the chief decolourant. Glass compositions of monochrome bowls, core-formed and mosaic glass vessels are very similar, despite the different forms, colours and manufacturing techniques of the vessels.

Conclusions: While the production centre for the Jebel Khalid glass remains elusive, the similarity to other published Hellenistic glasses from Greek mainland sites, Rhodes, Tel Anafa in Israel, and Gordion in central Turkey, indicates a tightly controlled composition with comparable batch ingredients. Without more comparative material of this date from the Near East and Greece, it is difficult to determine whether production of the vessel glass from this Seleucid site in the Near East occurred in the Aegean region or the Syro-Palestinian Levant, or both. Vessel style and archaeological context lean towards an Aegean connection, but until more comparative glass is analysed, and trace element and isotope data are considered, questions of primary and secondary production remain unresolved.

Keywords: Glass, Composition, Electron probe microanalysis, Jebel Khalid, Syria, Hellenistic, Greece, Seleucid, Chemical analysis

Introduction, background and aims

Jebel Khalid

The opportunity to examine archaeological material from a well-dated, single-period site is rare and valuable. This study deals with the chemical characterisation of glass vessels from a late 1st millennium BCE Greek garrison city in Syria. Jebel Khalid was a fortified settlement situated strategically on the west bank of the Euphrates River in northern Syria (Fig. 1). It dates to the early years of the 3rd century BCE, at the beginning of Seleucid control of the region in the Hellenistic period following the conquests of Alexander the Great. The town was inhabited for approximately two centuries until it was largely abandoned by the late 70s BCE, when the Seleucid Empire collapsed [14: p. 97]. An Australian team excavated the site from 1984 until 2011, uncovering a large corpus of material that is revealing information about the lives and interactions of the inhabitants of the settlement. This

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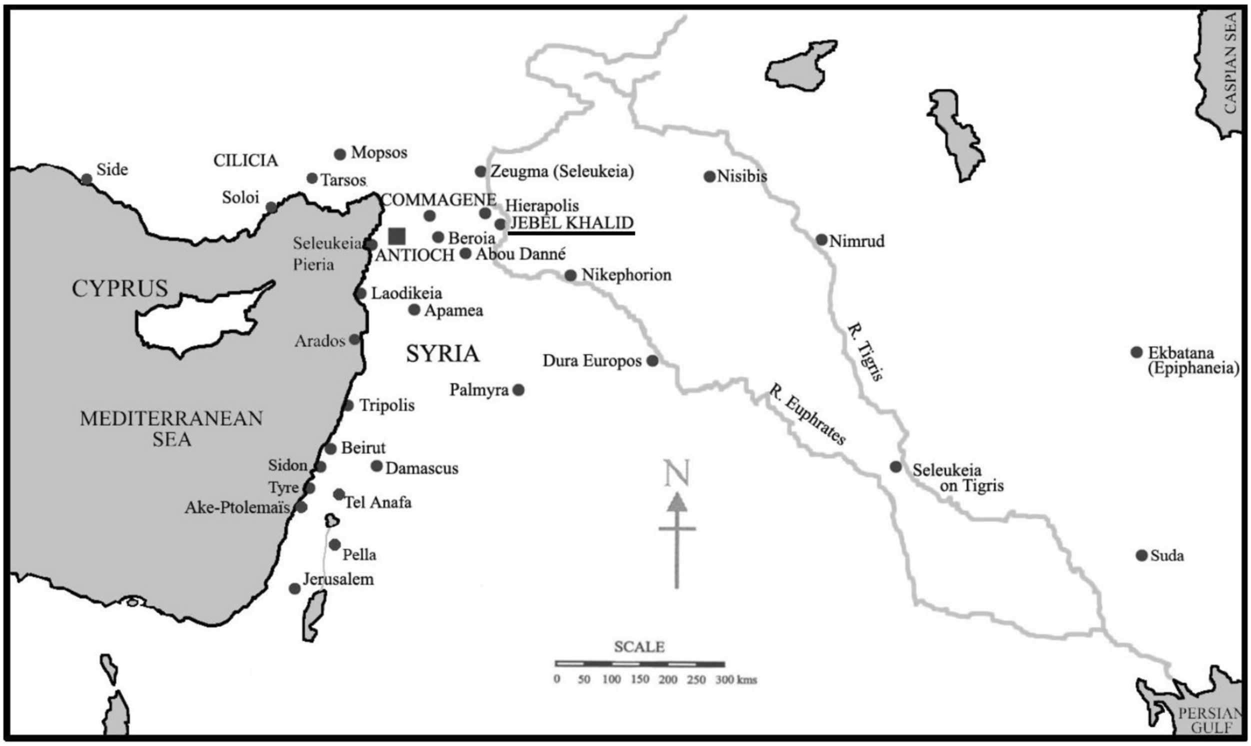

Fig. 1 Map showing the location of the site of Jebel Khalid on the Euphrates River. Map is provided courtesy of Prof. Graeme Clarke (Australian National University)

study presents preliminary results of SEM-WDS chemical compositional analyses of a selection of the numerous glass vessels found on the Acropolis area of the site.

During the 3rd century BCE, early in the site's occupation, a two-storied administrative public building, or palace, was constructed on the Acropolis. Architecturally this building appears to be Greek, but it also has features that belong rather to the Mesopotamian/Achaemenid tradition of palace design [12: pp. 25–48]. The main reception halls of this building were each equipped with two large kitchens on either side. The substantial amount of repetitive pottery and glassware recovered is indicative of mass dining and drinking, perhaps by the governor and his garrison troops in Macedonian style [14: pp. 101–102]. Below the Acropolis, the rest of the site included a temple, public buildings and domestic housing, surrounded by a circuit wall.

The glass

The glass sampled for this study comes from 59 vessel fragments unearthed between 1988 and 1996 in excavation trenches across the Acropolis administrative building, and dates typologically between the late 2nd and early 1st centuries BCE [40: pp. 245–246]. This is the period when most of the site was abandoned, and represents material from the latest occupation. The vessel types and colours analysed in this study are representative of those excavated from the Acropolis administrative complex. The vessels sampled were predominantly monochrome bowls, cast by sagging or slumping over a clay or stone former mould, with a small number that could be identified as petal-decorated, fluted, cast-footed, or carinated. Many of the plain bowls were decorated with internal and external wheel-cut horizontal grooves. The monochrome bowls are likely to have been drinking cups [21: p. 193], and were the predominant form of glassware used in the Hellenistic world prior to the advent of blown glass vessels in the Roman 1st century BCE [40: p. 245]. The external cut petal motifs and vertical flutes were based on Achaemenid metal prototypes [41: p. 44, 42: p. 142].

In addition to the monochrome bowls, two mosaic-cane bowls JK01 (GN31) and JK04 (GN22), and one core-formed alabastron, JK26 (GN26), are included in this study. Both mosaic bowls have spiral canes like the mosaic cane bowls found in the Antikythera shipwreck, dated 80/50 BCE, with parallels dated from the mid 2nd century to the early 1st century BCE [40: p. 258, 63: pp. 34–37]. JK01 was made of translucent emerald green with spiral canes of dark green, and opaque yellow or pale yellow-green. The mosaic glass of sample JK04 consisted of very dark blue and opaque yellow swirled canes in a dark blue matrix. The core-formed vessel had a dark blue matrix with opaque yellow and opaque white trail decoration. Although core-formed vessels were the most numerous group of glass vessels produced in the 3rd to early 2nd centuries BCE, they were rare in domestic contexts [42: pp. 144–145].

The vessel forms and visually identified colours of the sampled glasses are summarised in Table 1.

Aims

The open, sagged bowl forms of the late Hellenistic period in the Levant have a restricted range of colours and forms, categorised by Grose [20: pp. 54, 56, chart, 21: p. 193, Fig. 110] into conical, parabolic, hemispherical and shallow hemispherical forms. The preference for deep hemispherical bowls over conical bowls has been seen as reflective of Greek Seleucid rather than North Syrian taste [41: p. 48]. The broad visual uniformity of the colour, form and decoration of the plain bowls across the eastern Mediterranean provides little distinction by which to identify centres of production, distribution patterns, or regional traits. Where physically distinctive identifiers are lacking, it was the aim of this study to employ chemical compositional data to characterise an otherwise universally bland glass production.

Chemical characterisation of the glass was also used to identify differences and similarities between the monochrome glass, both decorated and plain, and the mosaic and core-formed glasses. All were produced and used simultaneously in this period, both at Jebel Khalid and in the wider Hellenistic Mediterranean world. Based on physical typology and distribution patterns, O'Hea [41: p. 48] suggested that the glassware at Jebel Khalid could have been locally or regionally supplied, although the mosaic cane bowls showed a taste for imported fine glassware not seen elsewhere in the Levant away from the coast, and which Jackson-Tal [30: p. 27] suggested could indicate that they were imported from Alexandria or the Aegean (see also [38]). Comparison of the compositional data from the current study with published data from analyses of Hellenistic glasses from other sites, aimed to set the Jebel Khalid glasses in the broader context of Mediterranean vessel glass.

There is also a high proportion at Jebel Khalid of colourless—that is, intentionally decoloured—glass, presumably in imitation of much admired rock crystal, as described by Pliny in his Natural History (e.g. 37.33.111-12). It is possible that the darker green and amber glasses were deliberately coloured to imitate bronze vessels [41: p. 48]. The current analysis of the Hellenistic vessel glasses from Jebel Khalid aimed to investigate these visual distinctions of form, style and colour by characterising and comparing their chemical compositions.

Results

General characteristics

The results of the electron microprobe (SEM-WDS) compositional analyses of 59 samples of transparent glass from the Jebel Khalid Acropolis are reported as oxides in Table 1. Ancient glass was typically made of silica from sand or quartz pebbles, combined with a soda flux derived from either plant ash or mineral soda (natron), and lime as a stabiliser [3, 22, 51, 54, 61]. Lime was probably introduced to the mineral soda glass batch in combination with the silica sand source (e.g. [22: p. 277, 61]).

After the second millennium BCE, west of the Euphrates glass was predominantly fluxed with mineral soda, or natron, until the 9th century in the Islamic period, when plant ash was used again [22: pp. 271–276, 51: p. 1825, 55]. Ash had continued to be used east of the Euphrates River in Mesopotamia and Iran throughout this time [24: p. 204, 58: pp. 1284–1285].

To this basic silica-soda-lime mix could be added modifying agents that produced colour, removed colour to form colourless glass, or opacified glass. Comparative analysis and interpretation of compositional glass data is initially based on the essential raw materials, the so-called reduced glass composition that excludes intentionally added modifiers such as colourants and opacifiers, and includes the basic glassmaking oxides and their associated 'contaminant' oxides. Besides silica, soda and lime which are the major components, magnesia, potash and phosphorus are typically minor impurities associated with a plant ash soda flux, while iron, titania and alumina may enter the glass as natural sedimentary contamination of the silica sand source [8, 11, 16, 25, 36, 37, 61: p. 162T]. Alumina may also be derived from the refractory containers used in glass production [47, 61: p. 175T].

From data obtained for the 13 analysed oxides (Table 1), it was found that the silica content of the glass ranges from approximately 64–74 % (average 68.22 %), while soda is present at levels of approximately 15–19 % (average 17.35 %). Lime levels range widely between approximately 5.6 and 10 %, with the majority falling between 8 and 10 %. The average lime content overall is 8.31 %. All but two Jebel Khalid samples therefore have a typical soda-silica-lime composition, which can be characterised as low-magnesia, low-potash (LMLK), with values below 1.4 % for both oxides. Combined with low phosphorus levels of less than 0.19 % (average 0.10 %), this indicates the use of a natron or mineral soda flux [54].

The presence of elevated levels of potash, magnesia and phosphorus would indicate, on the other hand, that glasses were fluxed with plant ash rather than with mineral soda [3, 8; p. 277, 58]. Glasses fluxed with mineral soda typically contain potash and magnesia at concentrations less than 1.5 % [17]. It is of interest that two

Table 1 Form, type series, colour and analytical data for Jebel Khalid glass included in this study

Sample	Form	Type series	Colour	Na_2O	SiO_2	MnO	TiO_2	MgO	K_2O	FeO	CaO	Al_2O_3	P_2O_5	CoO	Sb_2O_3	CuO	Total
JK01	Mosaic cane bowl	31	op yl, yl-gr, em gr, gr*	16.86	65.69	0.80	0.06	0.61	0.92	0.61	8.56	2.23	0.11	0.00	0.04	1.40	97.90
				0.14	0.19	0.01	0.00	0.01	0.01	0.00	0.03	0.02	0.01	0.00	0.01	0.02	
JK02	Fluted sagged bowl	10	dk amb	18.22	67.53	0.02	0.06	0.58	0.84	0.36	8.40	2.35	0.12	0.00	0.08	0.01	98.56
				0.06	0.23	0.01	0.01	0.01	0.01	0.01	0.04	0.02	0.01	0.00	0.01	0.00	
JK03	Sagged bowl	24	amb	18.52	69.40	0.61	0.04	0.40	0.69	0.28	6.29	2.18	0.05	0.00	0.06	0.00	98.52
				0.15	0.50	0.01	0.00	0.01	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.01	
JK04	Mosaic cane bowl	22	bl, yl, dk bl*	16.58	64.82	1.27	0.06	0.61	0.83	0.56	8.19	2.16	0.12	0.00	0.06	1.96	97.23
				0.13	0.11	0.01	0.01	0.01	0.05	0.01	0.01	0.02	0.01	0.00	0.01	0.05	
JK05	Shallow sagged bowl	18	lt gr	19.27	66.88	0.08	0.05	0.53	0.59	0.35	8.16	2.04	0.08	0.00	0.06	0.01	98.11
				0.05	0.20	0.00	0.00	0.02	0.01	0.01	0.06	0.03	0.01	0.00	0.00	0.00	
JK06	Hemispherical	5	lt bl/aqua	18.14	66.29	0.18	0.06	0.59	0.81	0.44	8.92	2.42	0.11	0.00	0.07	0.01	98.02
	Sagged bowl			0.03	0.25	0.04	0.01	0.01	0.01	0.02	0.05	0.03	0.01	0.00	0.01	0.01	
JK07	Sagged bowl	29	lt olive gr	15.96	68.39	0.90	0.06	0.76	0.92	0.37	8.79	2.16	0.14	0.00	0.07	0.00	98.54
				0.08	0.20	0.00	0.00	0.01	0.01	0.01	0.04	0.01	0.01	0.00	0.01	0.01	
JK08	Petal-decorated bowl	2	v lt gr	17.78	68.22	0.83	0.05	0.61	0.91	0.37	7.58	2.40	0.10	0.00	0.08	0.00	98.94
				0.12	0.21	0.01	0.00	0.02	0.01	0.00	0.08	0.02	0.01	0.00	0.01	0.00	
JK09	Deep hemispherical	3	amb	19.32	66.37	0.10	0.05	0.63	0.53	0.35	9.80	2.05	0.07	0.00	0.05	0.00	99.34
	Sagged bowl			0.10	0.32	0.01	0.01	0.02	0.00	0.00	0.02	0.01	0.02	0.00	0.01	0.00	
JK10	Sagged bowl	–	col	16.92	67.68	1.13	0.06	0.59	0.66	0.45	9.01	2.33	0.10	0.00	0.05	0.00	98.99
				0.09	0.19	0.01	0.00	0.01	0.06	0.00	0.06	0.01	0.00	0.00	0.01	0.00	
JK11	Cast footed bowl	23	v lt gr	18.59	67.58	0.15	0.05	0.55	0.49	0.36	9.10	2.23	0.09	0.00	0.05	0.00	99.24
				0.02	0.43	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00	0.01	0.00	
JK12	Fluted sagged bowl	10	amb	18.52	68.05	0.02	0.06	0.59	0.84	0.37	8.42	2.37	0.14	0.00	0.07	0.00	99.43
				0.11	0.13	0.01	0.00	0.02	0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00	
JK13	Sagged bowl	–	col	16.25	68.73	1.32	0.05	0.57	0.59	0.40	8.02	2.36	0.08	0.00	0.11	0.00	98.47
				0.11	0.07	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.01	0.00	
JK14	Sagged bowl	–	amb	17.17	69.50	0.50	0.06	0.69	0.64	0.39	8.08	2.35	0.09	0.00	0.05	0.01	99.54
				0.11	0.43	0.01	0.01	0.01	0.00	0.01	0.02	0.01	0.01	0.00	0.01	0.00	
JK15	Sagged bowl	–	gr col	17.55	67.19	1.96	0.06	0.64	0.62	0.42	7.95	2.17	0.07	0.00	0.05	0.01	98.68
				0.08	0.12	0.01	0.01	0.01	0.03	0.01	0.08	0.01	0.01	0.00	0.01	0.01	
JK16	Sagged bowl	–	amb	16.62	69.12	0.02	0.05	0.60	0.93	0.32	8.85	2.17	0.09	0.00	0.07	0.00	98.83
				0.10	0.17	0.00	0.01	0.01	0.01	0.01	0.04	0.02	0.01	0.00	0.01	0.00	
JK18	Sagged bowl	–	amb	18.98	68.93	0.59	0.04	0.41	0.67	0.27	6.14	2.19	0.05	0.00	0.06	0.00	98.33
				0.09	0.30	0.01	0.00	0.01	0.01	0.01	0.06	0.01	0.01	0.00	0.02	0.00	

Table 1 continued

Sample	Form	Type series	Colour	Na_2O	SiO_2	MnO	TiO_2	MgO	K_2O	FeO	CaO	Al_2O_3	P_2O_5	CoO	Sb_2O_3	CuO	Total
JK19	Conical sagged bowl	13	col	18.29	66.26	1.23	0.05	0.60	0.69	0.49	8.19	2.35	0.10	0.00	0.06	0.00	98.29
				0.10	0.40	0.01	0.00	0.01	0.00	0.01	0.09	0.02	0.01	0.00	0.01	0.00	
JK20	Sagged bowl	–	v lt gr	17.13	70.49	0.11	0.06	1.35	1.37	0.57	4.38	1.04	0.45	0.00	0.10	0.00	97.06
				0.11	0.39	0.00	0.01	0.00	0.02	0.01	0.09	0.02	0.01	0.00	0.01	0.00	
JK21	Footed bowl base	68	lime gr	18.16	64.89	0.33	0.06	0.90	0.65	0.36	10.05	2.07	0.19	0.00	0.05	0.00	97.71
				0.10	0.26	0.01	0.00	0.01	0.01	0.01	0.05	0.02	0.01	0.00	0.01	0.00	
JK22	Sagged bowl	–	lime gr	18.92	66.61	0.09	0.05	0.58	0.76	0.38	8.10	2.47	0.12	0.00	0.06	0.00	98.15
				0.10	0.68	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.00	
JK23	Sagged bowl	–	p	18.07	66.05	1.81	0.04	0.59	0.57	0.34	8.50	2.17	0.08	0.01	0.06	0.01	98.28
				0.11	0.23	0.02	0.01	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.02	0.00	
JK24a	Conical sagged bowl	7	amb	15.89	69.31	0.24	0.07	0.53	0.56	0.38	8.62	2.48	0.09	0.01	0.06	0.01	98.25
				1.12	0.32	0.00	0.01	0.01	0.01	0.02	0.06	0.06	0.01	0.01	0.01	0.00	
JK24b	Conical sagged bowl	7	gr	15.77	70.38	0.42	0.06	0.51	0.55	0.38	7.72	2.58	0.08	0.00	0.07	0.00	98.51
				0.11	0.18	0.01	0.00	0.02	0.01	0.01	0.02	0.02	0.03	0.00	0.01	0.00	
JK25	Sagged bowl	–	amb	15.69	69.00	0.22	0.05	0.65	0.60	0.32	10.11	2.07	0.08	0.00	0.05	0.01	98.86
				0.13	0.23	0.01	0.01	0.01	0.02	0.00	0.08	0.03	0.03	0.00	0.02	0.02	
JK26	Core-formed alabastron	26	op yl, op wh,	15.89	70.94	0.03	0.05	0.50	0.66	0.57	7.78	2.22	0.08	0.08	0.07	0.12	98.99
			dk bl*	0.09	0.46	0.01	0.02	0.02	0.01	0.02	0.08	0.04	0.02	0.01	0.01	0.01	
JK28	Deep sagged bowl	3	lt amb	15.90	74.25	0.01	0.04	0.25	0.48	0.23	5.60	1.87	0.08	0.00	0.03	0.00	98.75
				0.08	0.33	0.01	0.01	0.01	0.00	0.00	0.03	0.02	0.03	0.00	0.02	0.00	
JK29	Carinated sagged bowl	35	str gr	17.88	67.04	0.25	0.06	0.65	0.74	0.42	8.56	2.42	0.10	0.00	0.07	0.00	98.18
				0.14	0.13	0.01	0.01	0.01	0.00	0.01	0.02	0.01	0.03	0.00	0.01	0.01	
JK30	Shallow sagged bowl	42	amb	16.04	73.93	0.01	0.04	0.24	0.58	0.23	5.61	1.87	0.08	0.00	0.04	0.00	98.65
				0.21	0.15	0.00	0.00	0.00	0.01	0.00	0.04	0.01	0.01	0.00	0.01	0.00	
JK31	Sagged bowl	–	amb	17.01	70.75	0.02	0.05	0.42	0.80	0.28	6.92	2.28	0.09	0.00	0.06	0.00	98.67
				0.13	0.20	0.00	0.00	0.01	0.01	0.01	0.03	0.02	0.01	0.00	0.01	0.00	
JK32	Deep sagged bowl	3	col	17.12	67.22	1.57	0.06	0.65	0.66	0.47	8.57	2.33	0.10	0.00	0.08	0.00	98.84
				0.05	0.22	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.01	0.00	
JK33	Hemispherical	4	v lt gr	17.07	68.31	0.84	0.04	0.48	0.53	0.54	8.67	2.16	0.07	0.00	0.05	0.00	98.75
	Sagged bowl			0.09	0.14	0.01	0.01	0.01	0.01	0.01	0.08	0.02	0.01	0.00	0.01	0.00	
JK34	Sagged bowl	–	v lt bl/bl*	16.53	69.20	0.72	0.06	0.59	0.83	0.38	8.11	2.32	0.09	0.00	0.08	0.01	98.90
				0.09	0.23	0.02	0.01	0.01	0.02	0.00	0.04	0.00	0.01	0.00	0.01	0.00	
JK35	Cast footed bowl	23	gr col	17.78	68.22	0.67	0.04	0.43	0.95	0.28	7.54	2.22	0.07	0.00	0.22	0.00	98.43
				0.09	0.33	0.01	0.00	0.01	0.01	0.01	0.03	0.02	0.01	0.00	0.01	0.00	
JK36	Deep sagged bowl	3	v lt gr	17.17	68.17	0.84	0.05	0.48	0.52	0.53	8.63	2.15	0.07	0.00	0.06	0.00	98.69
				0.06	0.49	0.02	0.01	0.00	0.02	0.01	0.04	0.00	0.01	0.00	0.00	0.00	

Table 1 continued

Sample	Form	Type series	Colour	Na_2O	SiO_2	MnO	TiO_2	MgO	K_2O	FeO	CaO	Al_2O_3	P_2O_5	CoO	Sb_2O_3	CuO	Total
JK37	Deep sagged bowl	3	v lt gr	16.88	64.47	1.60	0.07	0.76	1.00	1.15	9.30	2.43	0.15	0.00	0.08	0.01	97.90
				0.30	0.13	0.02	0.00	0.03	0.01	0.01	0.10	0.03	0.01	0.00	0.01	0.00	
JK38a	Sagged bowl	–	amb	15.34	68.56	0.21	0.05	0.57	0.78	0.32	9.67	2.19	0.10	0.00	0.06	0.00	97.85
				0.10	0.15	0.02	0.01	0.01	0.01	0.01	0.03	0.01	0.00	0.00	0.00	0.00	
JK38b	Sagged bowl	–	amb	17.15	71.39	0.02	0.05	0.37	0.58	0.25	6.45	1.73	0.08	0.00	0.05	0.00	98.12
				0.12	0.30	0.01	0.01	0.00	0.01	0.00	0.06	0.02	0.01	0.00	0.00	0.00	
JK39	Fluted sagged bowl	10	amb	18.05	66.88	0.02	0.06	0.59	0.87	0.36	8.42	2.34	0.12	0.00	0.07	0.00	97.79
				0.04	0.08	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.02	0.00	
JK40	Deep sagged bowl	3	lt bl/aqua	17.55	67.05	0.20	0.06	0.54	0.63	0.44	9.09	2.37	0.09	0.00	0.06	0.00	98.08
				0.04	0.27	0.01	0.01	0.01	0.00	0.01	0.02	0.01	0.00	0.00	0.01	0.00	
JK41	Conical sagged bowl	7	str gr	18.65	65.83	0.37	0.04	0.58	0.71	0.37	9.10	2.20	0.09	0.00	0.07	0.00	98.02
				0.10	0.10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	
JK42	Conical sagged bowl	7	amb	17.92	69.73	0.03	0.06	0.38	0.58	0.34	6.80	1.92	0.12	0.00	0.04	0.01	97.94
				0.08	0.29	0.00	0.01	0.01	0.00	0.01	0.04	0.00	0.01	0.00	0.01	0.00	
JK43	Hemispherical	6	col	17.93	64.84	1.77	0.06	0.74	0.83	0.52	9.62	2.10	0.14	0.00	0.07	0.01	98.62
	Sagged bowl			0.07	0.25	0.01	0.01	0.01	0.02	0.00	0.05	0.01	0.01	0.00	0.02	0.00	
JK44	Shallow sagged bowl	18	amb	16.23	69.18	0.02	0.05	0.60	0.97	0.31	9.03	2.22	0.09	0.00	0.07	0.01	98.77
				0.14	0.13	0.00	0.01	0.00	0.01	0.01	0.10	0.02	0.01	0.00	0.03	0.00	
JK45	Sagged bowl	–	amb	18.65	65.81	0.02	0.05	0.63	0.53	0.35	9.89	2.19	0.10	0.00	0.05	0.00	98.28
				0.01	0.53	0.00	0.01	0.01	0.01	0.01	0.09	0.01	0.01	0.00	0.01	0.00	
JK46	Sagged bowl	–	gr col	16.34	68.76	1.37	0.10	0.63	0.57	0.54	7.41	2.54	0.09	0.01	0.05	0.00	98.41
				0.12	0.38	0.11	0.00	0.01	0.00	0.01	0.13	0.02	0.01	0.00	0.01	0.00	
JK47	Shallow sagged bowl	42	col	17.60	68.49	1.33	0.07	0.58	0.74	0.49	6.67	2.37	0.09	0.00	0.07	0.00	98.51
				0.11	0.15	0.02	0.01	0.00	0.01	0.01	0.04	0.02	0.02	0.01	0.02	0.00	
JK48	Shallow sagged bowl	42	amb	17.02	67.17	0.03	0.06	0.72	0.72	0.36	10.21	2.19	0.09	0.00	0.06	0.00	98.63
				0.04	0.10	0.00	0.01	0.01	0.00	0.01	0.04	0.01	0.01	0.00	0.02	0.01	
JK49	Deep sagged bowl	3	gr col	17.62	68.45	1.33	0.06	0.58	0.75	0.49	6.69	2.37	0.10	0.00	0.06	0.00	98.50
				0.09	0.28	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.00	0.01	0.00	
JK50	Sagged bowl	–	lt amb	17.13	70.92	0.02	0.05	0.44	0.85	0.27	7.02	2.30	0.09	0.00	0.07	0.01	99.17
				0.09	0.13	0.00	0.01	0.01	0.02	0.01	0.04	0.02	0.02	0.00	0.02	0.00	
JK51	Sagged bowl	–	col	15.75	69.79	1.28	0.06	0.71	1.17	0.34	7.59	2.17	0.10	0.00	0.09	0.00	99.05
				0.03	0.28	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.00	0.01	0.00	
JK52	Sagged bowl	29	col	17.02	71.20	1.46	0.08	1.10	1.10	0.71	4.34	1.22	0.24	0.00	0.13	0.00	98.60
				0.10	0.25	0.01	0.00	0.01	0.05	0.01	0.05	0.01	0.01	0.00	0.01	0.00	
JK53	Deep sagged bowl	3	bl col	17.85	66.61	0.43	0.05	0.65	0.58	0.37	9.92	2.07	0.12	0.00	0.07	0.00	98.71
				0.16	0.13	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.00	0.01	0.00	

Table 1 continued

Sample	Form	Type series	Colour	Na_2O	SiO_2	MnO	TiO_2	MgO	K_2O	FeO	CaO	Al_2O_3	P_2O_5	CoO	Sb_2O_3	CuO	Total
JK54	Sagged bowl	29	amb gr	16.81	68.88	0.47	0.04	0.57	0.63	0.32	8.94	2.18	0.07	0.00	0.05	0.00	98.97
				0.02	0.28	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00	
JK55	Sagged bowl	–	lt gr	17.83	66.77	0.43	0.05	0.66	0.71	0.37	10.06	2.06	0.12	0.00	0.06	0.00	99.11
				0.02	0.06	0.00	0.00	0.01	0.02	0.01	0.06	0.01	0.01	0.00	0.00	0.00	
JK56	Sagged bowl	–	gr col	18.57	66.10	0.36	0.05	0.62	0.78	0.39	9.29	2.23	0.11	0.00	0.06	0.00	98.56
				0.07	0.03	0.06	0.00	0.01	0.01	0.02	0.12	0.03	0.03	0.00	0.01	0.00	
JK57	Sagged bowl	–	lt gr	18.26	67.82	0.08	0.06	0.57	0.69	0.43	8.73	2.47	0.11	0.00	0.06	0.00	99.27
				0.08	0.22	0.00	0.01	0.02	0.00	0.00	0.04	0.02	0.01	0.00	0.01	0.00	
JK58	Sagged bowl	–	gr	17.62	69.81	0.43	0.05	0.47	0.85	0.27	7.04	2.21	0.10	0.00	0.07	0.00	98.92
				0.01	0.27	0.00	0.00	0.01	0.02	0.00	0.05	0.05	0.02	0.00	0.01	0.00	
JK60	Sagged bowl	–	lt bl/aqua	16.51	69.05	0.02	0.06	0.63	0.95	0.39	9.07	2.18	0.15	0.00	0.08	0.01	99.10
				0.09	0.22	0.00	0.00	0.01	0.01	0.02	0.20	0.01	0.01	0.00	0.01	0.01	

Compositional data are presented for each sample as average oxide weight percent data for replicate analyses (first row), and one standard deviation for the replicate analyses

TS = Type series. TS is referred to as Glass Number (GN) where published by O'Hea. Samples without TS number were not diagnostic, and could not be assigned to a type. They are identified as generic sagged bowls. Samples analysed were either taken from the published fragment or from fragments of the same type. These types are published in [40], with the exception of TS68 ([43: p. 160]) and TS42 (unpublished, details courtesy of M. O'Hea, pers. comm.)

JK38a and JK38b are two separate vessels

bl blue, *gr* green, *em* emerald, *amb* amber, *col* colourless, *yl* yellow, *op* opaque, *dk* dark, *lt* light, *v* very, *str* strong

* indicates the colour of glass analysed in multicolour glasses

samples, JK 20, a greenish-coloured bowl, and JK 52, a colourless bowl, possibly late in the series, exhibit lower lime concentrations at around 4.3 %, while their phosphorus contents are elevated to 0.45 and 0.24 % respectively. Combined with relatively higher levels of magnesia (1.35 and 1.10 %) and potash (1.37 and 1.10 %), this could suggest a different source of flux for these two samples, possibly including the addition of plant ash (e.g. [1; p. 241]).

The alumina values for the Jebel Khalid glasses are typical of sand-sourced silica glass, falling between 1.76 and 2.58 % (average 2.23 %), excluding the same two outliers which have lower alumina concentrations, JK20 (1.08 %), and JK52 (1.24 %) (Fig. 2). The iron oxide content of all glasses ranges from 0.23 to 0.71 %, excluding the higher concentration outlier, JK37 (1.15 %). Iron oxide concentrations are generally below 0.60 % (average 0.39 %). Titania is present in all samples between 0.04 and 0.10 %, and appears to be weakly correlated with iron ($R^2 = 0.4$) as a contaminant of the sand (Fig. 3). The levels of iron oxide, alumina and titania in the Jebel Khalid Hellenistic glasses are consistent with the use of impure, sand-sourced silica.

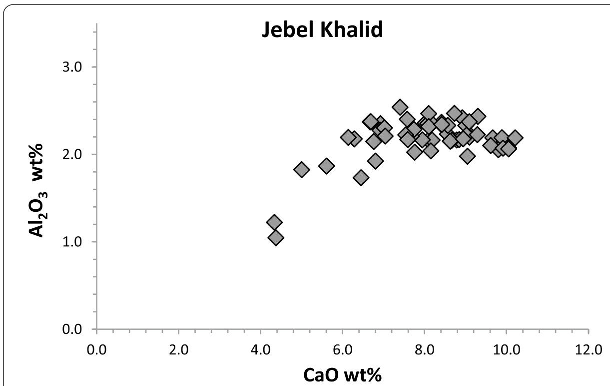

Fig. 2 Bivariate *plot* of lime vs alumina for Jebel Khalid Acropolis glass

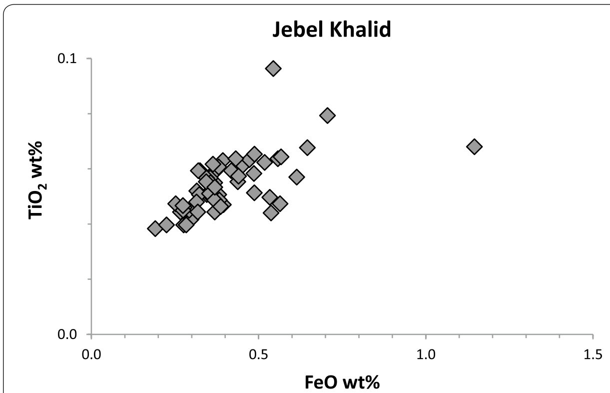

Fig. 3 Bivariate *plot* of iron oxide vs titania for Jebel Khalid Acropolis glass

The two main compositional outliers (JK20 and JK52) were identified because of their inconsistent levels of several key oxides, including lime, alumina, titania, potash, magnesia and phosphorus. Other samples of note are JK46, a greenish-coloured sagged bowl with relatively high titania (0.10 %), and JK21, a green, footed bowl base, with slightly high magnesia content (0.90 %). The majority of the glasses analysed form a tight group when oxides are plotted, regardless of colour, vessel form or type.

Colourants and decolourants

Before analysis, samples were assigned to visual colour groups distinguished as clearly as possible by eye to record the variability of colours produced from much less varied chemical compositions (Table 1). The production of colour is complex and is reliant on more than just composition (e.g. [2, 66]).

Copper and cobalt

The presence of cobalt oxide in glass produces a deep blue, and copper oxide may colour glass red, blue or green [2, 66]. Three of the blue and green glasses from Jebel Khalid owe their colours to the presence of these colourant oxides. The cobalt oxide concentration (0.08 %) for the blue sample from the core-formed alabastron, JK26, provides the source of the blue colour for this glass. Copper oxide was also detected in this sample at 0.12 %. It is well-known that cobalt can impart a deep blue colour to glass even at a concentration of a few hundred ppm (see for example [1: p. 244, 61: p. 163T, 66], and as little as 0.02 % [24: p. 69]). Kaczmarczyk and Hedges [33: p. 151] (see also [57: p. 289]) define a cobalt blue glass as one containing at least 0.05 % cobalt oxide.

In the Late Bronze and early Iron Ages cobalt colourant was predominantly sourced from the Western Desert oases of Egypt in the form of cobaltiferous alum. Glasses coloured with cobalt derived from alum are typified by raised concentrations of alumina, magnesia, iron, nickel, zinc and manganese [23, 32, 33: pp. 41–55, 35, 39, 44, 48, 50: pp. 267–268, see 55: p. 958, 56: pp. 145–146, 57]. These cobalt glasses generally contain lower lime than non-cobalt glasses [18; pp. 272–273, 54; p. 157]. After approximately the 7th century BCE the source of cobalt changed, and the concentrations of the impurities associated with cobaltiferous alum returned to average levels [32: pp. 373–374, 33: pp. 45–47, 53, 52: pp. 51, 54]. Various cobalt ores have been identified in the region, one being an arsenic-nickel cobalt ore known to have been used in glassmaking [19, 24: pp. 69–74].

The levels of iron, alumina, manganese and magnesia in sample JK26 are similar to those in the non-cobalt coloured Jebel Khalid glasses suggesting that the source of colourant was not cobaltiferous alum. LA ICP-MS analyses of the Jebel Khalid glasses confirm that the concentrations of nickel, zinc and arsenic were not elevated either, leaving the source of cobalt as yet unknown (H. Rutlidge, UNSW, unpublished data). Tite and Shortland [57: p. 289] observed that second millennium Egyptian glass coloured with cobalt may also have copper oxide present in the range of 0.02–1.3 %. It is interesting that sample JK26 contains 0.12 % copper oxide, within the range defined by Tite and Shortland that qualifies it as a co-colourant. Elevated cobalt and copper oxides occur also in blue glasses from the Hellenistic period from Gordion in Anatolia [46: p. 68], and from Pichvnari and Tsikhisdziri in Georgia [55: p. 958].

An elevated level of copper oxide is responsible for the blue colour of JK04 (1.96 %) and the green colour of JK01 (1.40 %), both mosaic cane bowls. Other green to pale greenish or pale bluish glasses do not contain a significant quantity of this colourant, and derive their colour from iron, introduced as an impurity in the glass raw materials in similar concentrations in all samples [2: pp. 35, 48, 143, 61: p. 180T, 66: pp. 91, 163–164].

Iron

The majority of sands contain iron as an impurity at usually less than 1 % [33: p. 36–41]. In natron glasses the inclusion of iron in the glass batch as an impurity in silica sand can be responsible for colouring raw glass at levels below 0.5 % (e.g. [29: p. 151, 53]). The colouring effects of iron are complex, depending on its oxidation–reduction equilibrium. Colours produced include blue, green, yellow and brown [2: pp. 143, 155, 66: pp. 89ff, 119–120].

The best way for glassmakers to have avoided the colouring effects of iron was to use pure raw materials, because the use of sand in natron glasses commonly incorporated iron. Colourless glass could also be achieved by adding a decolourant [28: p. 764, 66: p. 97].

Iron oxide concentrations of the Jebel Khalid glass range between 0.23 and 1.15 % (average 0.41 %) and would have imparted the translucent greenish hue, or pale aqua blue due to the presence of ferrous ions (Fe^{2+}), while the presence of ferric ions (Fe^{3+}) in combination with sulphur can produce a dark brown or amber colour in a silica-soda-lime melt under strongly reducing conditions. Sulphur, although not measured in these analyses, is introduced intentionally or as contamination in one or more batch materials, including natron, or from the addition of organic materials and smoke from combustion that produces a reducing atmosphere [2: pp. 85ff, 155, 53: pp. 199, 206–207, 66: pp. 119–120, 240].

Of the 22 amber glasses analysed, the iron oxide content of all but one was low, falling between 0.23 and 0.39 %. The majority of the remaining 23 monochrome glasses in various shades of green, blue, purple and colourless had on average slightly higher iron oxide concentrations ranging up to 0.71 %, average 0.44 %. Sample JK37, from a very light green bowl, has an unusually high iron content (1.15 %), but despite a high manganese content of 1.63 %, it was not completely decoloured.

All but one of the glasses have a similar iron content, and this oxide is probably responsible for producing the various shades of green and light blue. In the absence of other identifiable colouring agents, the amber colour is likely due to the formation of the ferri-sulphide complex in a reducing atmosphere [2, 66]. Iron colouration is counteracted in the colourless glasses by manganese.

Antimony and manganese

Antimony was used from the early 1st millennium BCE, and into the Roman period as a decolourant, an opacifier, and as a fining agent to remove small seeds and bubbles in glass production [2: p. 80, 6: p. 116, 50: p. 272, 61: p. 179T, 66: pp. 116, 118, 121].

By the later Hellenistic period of the late 1st millennium BCE, manganese had come into use as a glass decolourant, and this is borne out by the compositional data of the Jebel Khalid glasses (see also [15: p. 95, 24: p. 246]). Manganese reacts with the iron impurities in the glass melt to counteract the iron-induced green tint by oxidation, producing a colourless glass instead [2, 7: p. 277, 28: p. 764, 66: p. 116]. Jackson [28: pp. 765, 771] noted the increasing use of manganese, rather than antimony, to around 1 % towards the end of the Roman period, defining deliberate addition of this oxide at levels exceeding 0.5 %, in agreement with Brill [7]. Under certain conditions manganese will not decolour, but will produce purple glass [2: p. 50, 66: p. 121], and may also act as a fining agent [61: p. 179T, 66: p. 130].

The low antimony oxide values for most of the Jebel Khalid glasses, including the colourless samples, fall below 0.09 %. Greenish to colourless glasses with slightly elevated antimony levels include colourless JK13 (0.11 %) and JK52 (0.13 %), greenish JK20 (0.10 %), and greenish colourless JK35 (0.22 %).

The eight truly colourless (untinted) samples, including JK13 and JK52, appear to be decoloured by elevated concentrations of manganese oxide, between 1.13 % and 1.77 %. Imperfectly decoloured greenish colourless samples JK15, JK46 and JK49 also have elevated levels of manganese between 1.33 and 1.96 %, and some shades of green, amber and light blue have levels of manganese oxide between 0.5 and 1 %. It is evident from these results that manganese oxide was the predominant glass decolourant in Jebel Khalid glasses (Fig. 4). The sagged

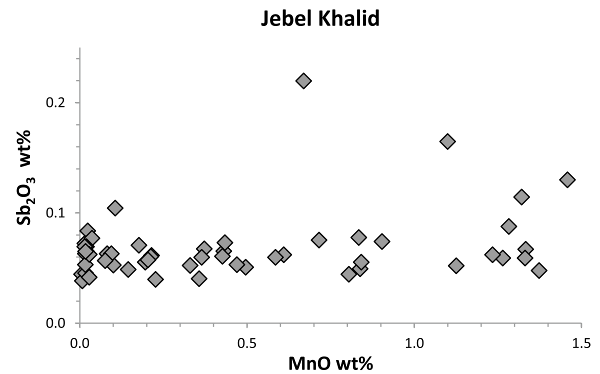

Fig. 4 Bivariate *plot* of manganese oxide vs antimony oxide for Jebel Khalid Acropolis glass. This figure illustrates the predominance of manganese as a decolourant over antimony

bowl sample, JK23, has a manganese oxide level of 1.84 %, which has resulted in purple colouration, rather than decolouration. All of the amber coloured samples have uniformly low manganese oxide concentrations (<0.61 %), with the majority containing less than 0.04 % manganese, and little or no antimony.

Discussion

Examination of the Acropolis glassware from Jebel Khalid gives insight into one particular part of life in a Greek city in the Near East, and as an elite area, the Acropolis is more likely to have been aligned with Greek tradition. The inhabitants of this area clearly enjoyed a Greek lifestyle with imported Greek wares. This is in contrast to some of the more local Syrian Iron Age influences seen in cooking wares [14: p. 108]. Both the island of Rhodes and mainland Macedonia have been identified as possible production centres for glass drinking vessels of Greek forms in the 3rd century BCE (see for example [59: p. 13]), and distribution patterns of later Hellenistic decorated bowls could suggest that at least some workshops were based on the Greek mainland or islands, according to O'Hea [42: p. 142].

Examination of the ceramic corpus at Jebel Khalid revealed that Greek shapes dominate both the imported wares and the local production of tableware, with few imports, which copy Greek shapes, from Mesopotamia or the south. As Clarke and Jackson pointed out [14: p. 107], the inhabitants of the housing insula were dining in Greek style, and drinking wine imported from Rhodes, as evidenced by the Rhodian amphora handles excavated [13: p. 288]. This is significant in view of the observed similarity of glass compositions from Rhodes, mainland Greece and Jebel Khalid at this time. Unfortunately, there is little to compare with in the way of contemporary compositional data from the Near East.

The vertically-fluted and petal-decorated bowls that developed in the Greek world from the Early into the Late Hellenistic periods, appeared in domestic glass assemblages during the early 1st century BCE. It is supposed that these later Hellenistic bowls were used for the same purpose as the similar forms of the plainer, earlier drinking bowls. Based on distribution patterns, O'Hea argued that these carved bowls could have been produced on the Greek mainland or islands, and seem to have been distributed to Asia Minor and the Near East as a result of Hellenised taste in the Levant in the 2nd to early 1st centuries BCE [42: pp. 142–143, 43: p. 154]. Petal-decorated JK08 (GN2) and fluted JK02, JK12 and JK39 (GN10) are examples of these types found at Jebel Khalid [40: pp. 245–254]. The cast fluted bowls belong to a series of Aegean Hellenistic cast bowls that imitated Greek metalware and are found for example on Delos, in the Athenian Agora and on Cyprus. Very few examples have been found in Eastern locations, such as Tel Anafa [40: p. 256, 43: p. 256]. Based on this evidence, O'Hea questioned Grose's [21: p. 194] attribution of this type to a Syro-Palestinian origin.

While the identification of secondary production centres has not been possible so far, circumstantial evidence suggested that fluted bowls were a product of Greece or the Aegean, and the similarity in the chemical composition of the fluted and petal-decorated glasses with those of the glasses excavated from Greek sites, including Rhodes, might support the suggestion that these were imports from the Greek Aegean region into the Near East. This is further supported by the findings of Reade et al. [45] who made similar observations with regard to the compositions of monochrome Hellenistic glassware found at Gordion in Anatolia.

The current analyses have also shown that the natron base-glass compositions of the Jebel Khalid fluted and petal-decorated glasses are the same as those of the undecorated bowls, and by this association we can contemplate the possibility that all the Jebel Khalid glass bowls were manufactured in Greece or the Aegean. At Rhodes, the so-called sagged bowls lack the internal grooves found on many Jebel Khalid glass bowls [42: p. 147]. Although this could suggest a different source of bowls from those found in the Levant, the similarity at least of the basic glass composition between Greek/Rhodian examples and those from Jebel Khalid, Tel Anafa (Israel), and Gordion (Anatolia) to the east might indicate another possibility: that the glass was made in the same place, but was formed elsewhere from imported raw glass chunks, or, alternatively, that the blank bowls were made in one place, whereas the cutting was done at a later stage somewhere along the route of distribution.

The dating of the cast dishes with footed bases, JK11 and JK35 (GN23), is difficult because of the similarity to the early 1st century CE series [21: pp. 186–187, 40: pp. 256–257]. O'Hea argued that there are comparative examples of 1st century BCE footed mosaic bowls that might allow an earlier dating for the Jebel Khalid samples. The two samples analysed in this study are closely similar in composition to the more securely dated 2nd to mid-1st century BCE Hellenistic bowls from the site, and to comparable Greek and Rhodian glass dating throughout the Hellenistic period. So consistent is the general composition of glass made at this time, that it does not provide a tool for more precise dating.

Analysed glass that was not monochrome includes two mosaic cane bowls, JK01 (GN31) and JK04 (GN22). A region of green colour analysed from JK01 was found to be relatively enriched in copper. The region of blue matrix from JK04 was coloured by elevated copper levels, while the dark blue matrix of the core-formed alabastron, JK26 (GN26), was found to be coloured by elevated levels of both cobalt and copper. Despite the different manufacturing techniques employed to make these vessels, and their different forms and colours, they are chemically similar to the various types of monochrome bowl when comparing reduced glass composition.

Inter-site compositional comparisons

The chemical compositions of glass from Hellenistic sites in Greece, Anatolia and the Levant (Table 2) deserve detailed examination and comparison with those of Jebel Khalid glass. Reduced or base glass compositions re-summed to 100 % were used to compare data between sites. Comparative sites, glass types, dates and source publications are presented in Table 2.

Comparison of the Jebel Khalid glass compositions with published analyses of early to late Hellenistic monochrome glass from the mainland Greek sites of Vergina and Pydna in Macedonia, Pherai in Thessaly, and from Gordion in central Anatolia, and Tel Anafa in modern Israel, show that the Jebel Khalid glass compositions are consistent with those of other Hellenistic glasses of the eastern Mediterranean region.

There has been much speculation about the location of primary glass production and secondary glassworking centres in the eastern Mediterranean. This is based largely on typological comparisons of excavated vessels, but lack of physical evidence makes this a difficult task. The island of Rhodes is the only identified manufacturing site yet discovered from this period, and is considered to have been the production site of glass for core-formed vessels from the 6th century BCE [49, 59, 60, 64]. Glassmaking tank furnaces exist at Beirut 015 but are dated to the early Roman period before 50 CE and possibly as early as the 1st century BCE [34]. Evidence is lacking for primary glass production in the early and middle Hellenistic Levant [24: p. 217]. The Levantine coast was certainly important in pre-Hellenistic and post-Hellenistic Roman glass production (e.g. [7: pp. 265–267, 30: p. 11, 34]), and there is no reason to believe that this would not have been the case through the Hellenistic period as well. Brems et al. [5: p. 2898] noted the view that during the Late Roman and Byzantine periods raw glass was produced exclusively in Egypt and Syro-Palestine, but for the earlier Hellenistic and Roman periods primary production probably also took place in other areas.

Reduced data for all glasses were compared using bivariate plots. Most of these LMLK glasses form a tight group when concentrations of magnesia and potash are considered (Fig. 5) with the following observations: the Pherai, Pydna and Rhodes Bead Factory samples have higher average potash than other glasses, including the Rhodes Necropolis, while the Tel Anafa glasses have higher average magnesia than those from Jebel Khalid, Pherai or Gordion. Connolly et al. [15: p. 93] noted the distinction between Tel Anafa and Pherai glasses which form distinct groups when plotted together. The Jebel Khalid glasses are slightly different again, although they overlap both groups, and all groups have outliers.

Concentrations of lime range relatively widely, while silica and alumina have comparable ranges, although

Table 2 Comparative glass from eastern Mediterranean sites

Site	Date	Glass description	Publication
Vergina (Macedonia, Greece)	c. 340 BCE	Colourless inlays	[8]: pp. 51–52; [9]: p. 65
Gordion (central Anatolia)	c. mid 4th–early 2nd C BCE	Monochrome beads and vessels	[45]
Pydna (Macedonia, Greece)	c. 300–290 BCE	Colourless vessels, plate	[26]
Bead factory (Rhodes)	Late 3rd–2nd C BCE	Cullet, canes, beads, vessels	[8]: p. 51; [9]: pp. 63–64
Pherai (Thessaly, Greece)	3rd–1st C BCE	Colourless	[15]
Rhodes Kakoula property	c. 175–150 BCE	Waste raw and acqua glass cullet	[49]
Tel Anafa (Israel)	c. 150–75 BCE	Monochrome bowls	[8]: p. 53; [9]: p. 67
Rhodes Necropolis	2nd–1st C BCE	Cast monochrome bowls, cullet	[10]: pp. 48, 115

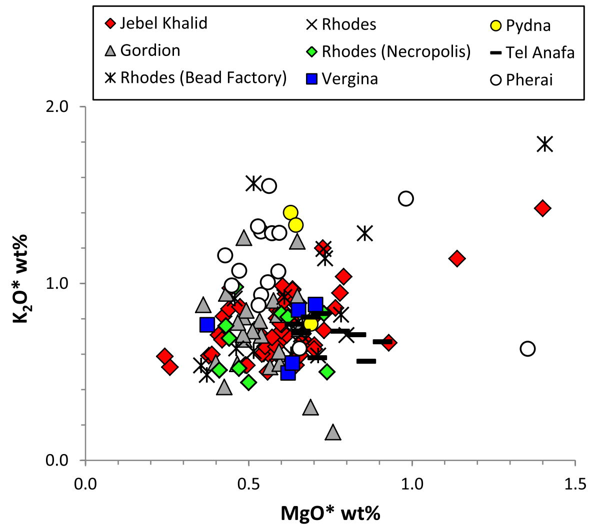

Fig. 5 Bivariate *plot* of magnesia vs potash for glasses from Jebel Khalid and comparative Hellenistic glasses. Comparative glass data were used from the sites of Gordion, Rhodes, Pydna, Vergina, Pherai and Tel Anafa. Reduced and re-summed glass compositions were used to compare data between sites (indicated by *asterisks*). Comparative glass references are provided in the text

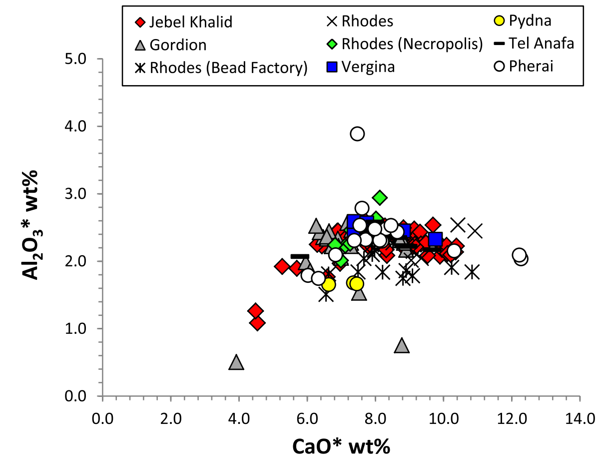

Fig. 6 Bivariate *plot* of lime vs alumina for glasses from Jebel Khalid and comparative Hellenistic glasses. Comparative glass data were used from the sites of Gordion, Rhodes, Pydna, Vergina, Pherai and Tel Anafa. Reduced and re-summed glass compositions were used to compare data between sites (indicated by *asterisks*). Comparative glass references are provided in the text

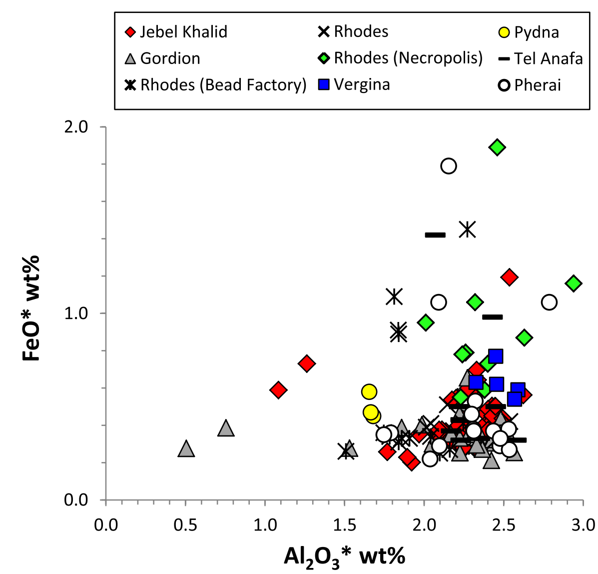

Fig. 7 Bivariate *plot* of alumina vs iron for glasses from Jebel Khalid and comparative Hellenistic glasses. Comparative glass data were used from the sites of Gordion, Rhodes, Pydna, Vergina, Pherai and Tel Anafa. Reduced and re-summed glass compositions were used to compare data between sites (indicated by *asterisks*). Comparative glass references are provided in the text

there are two lower level alumina glasses from Jebel Khalid, as noted above (JK20 and JK52), and two from Gordion (Fig. 6). Alumina contents are less variable than those of iron oxide. Pydna and Rhodes Bead Factory glasses on the whole contain less alumina, and Jebel Khalid, Tel Anafa, Gordion and most of the Pherai glasses group tightly when alumina vs iron oxide is considered (Fig. 7). Some of the Rhodes Necropolis and Kakoula glasses group here too, but they range more widely in iron oxide and alumina content overall.

Iron oxide levels are tightly grouped for most glasses from Jebel Khalid, Gordion, Tel Anafa, Pydna and to a lesser extent Vergina. The glass from Vergina is a little earlier in date and has slightly higher concentrations of iron on average. Four of the fourteen glass samples from the Rhodes Bead Factory, two from Tel Anafa, and one from Jebel Khalid have noticeably higher iron levels. Elevated iron would appear to be associated with the cobalt colourant in the Rhodian and Tel Anafa glasses, while the Jebel Khalid sample is from the dark green mosaic glass (JK01). Several of the Rhodes bowls from the Necropolis and three samples from Pherai have relatively high levels of iron, but this is not related to cobalt. The remainder of the Rhodian glasses from all three sample sets group closely with the other glasses. The Gordion glasses have consistently low iron concentrations, and most of the Jebel Khalid, Tel Anafa and Pherai glasses group closely with them.

While soda concentrations range between approximately 16–20 % for the majority of glasses, there are some exceptions. The Rhodes waste raw glass and cullet (Kakoula Property), some of the Bead Factory glass, some of the Pherai samples, and one Tel Anafa glass are comparatively low in soda (Fig. 8). Glasses are characterised by a range of lime content, with the lowest lime glasses being those from Gordion and Jebel Khalid. There

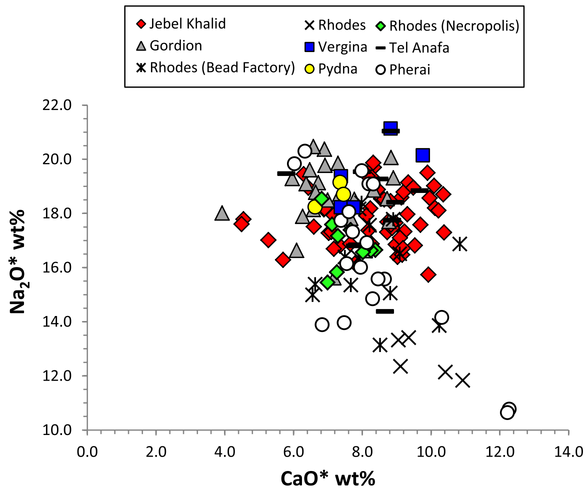

Fig. 8 Bivariate *plot* of lime vs soda for glasses from Jebel Khalid and comparative Hellenistic glasses. Comparative glass data were used from the sites of Gordion, Rhodes, Pydna, Vergina, Pherai and Tel Anafa. Reduced and re-summed glass compositions were used to compare data between sites (indicated by *asterisks*). Comparative glass references are provided in the text

is a grouping of glasses with similar lime concentration between approximately 6–8 %, which includes most glasses from Pherai, Gordion, Pydna and Rhodes Bead Factory, while the majority of glasses from Jebel Khalid, Tel Anafa, Rhodes Kakoula and half of the Vergina samples group between 8–10 % lime.

The earlier colourless glasses from Vergina, Pydna and Gordion (mid 4th–early 2nd century BCE) were decoloured with antimony, which is at variance with the manganese decolourant process practiced in the production of later colourless glass from Tel Anafa, and for most colourless glass from Jebel Khalid (mid 2nd–early 1st century BCE). Pherai and the Rhodes Bead Factory group, slightly earlier than and contemporary with Tel Anafa and Jebel Khalid, have samples fully decoloured with antimony. From the Rhodes Necropolis bowls group there is only one sample decoloured with antimony, while another two contained both decolourants (i.e., antimony and manganese). There are samples from the Rhodes Bead Factory and one from Pherai that contain both antimony and manganese, seen also in four glasses from Jebel Khalid. If the elevated concentrations of both antimony and manganese in colourless samples JK13 and JK52, and in imperfectly decoloured samples JK20 and JK35, were intentional, this might suggest several scenarios. (1) It is possible that both decolourants were added to achieve colourless glass. (2) The cullet used to make the vessels was acquired from two different traditions, from more than one source, and was mixed together (for examples of ancient Hellenistic cullet see [8: p. 51, 10, 49]), possibly as a result of recycling [10: p. 284, 15: pp. 95–96, 28: pp. 771–772]. The presence of lead suggested recycling in other Pherai glasses ([15: p. 94]; see also [27]). (3) The inclusion of antimony could also have been intended for the purpose of fining of the glass melt. Jackson [28: p. 705] noted that antimony is usually found only as a trace in glassmaking raw materials, so to be at detectable levels it must have been intentionally or coincidentally added, perhaps due to the mixing of different cullet from two different colourant traditions, either as a result of recycling, or of the mixing of raw glass from two different contemporary primary production centres.

By the date of the Rhodes Necropolis bowls group, and the Jebel Khalid and Tel Anafa glass, all from the mid-2nd/2nd century BCE, manganese decoloured glass was being produced, although the evidence indicates that both technologies still existed side by side. Jebel Khalid, Tel Anafa and the Rhodes Necropolis bowls group respresent later Hellenisitic glasses, and it is here that we can observe the transition from the long 1st millennium BCE antimony tradition to the manganese decolourant tradition that was to persist into the 1st millennium CE. It is likely that at the end of the 3rd century BCE we are seeing an overlap, and occasional mixing, of the two technologies. It is intriguing to observe that the use of antimony or manganese as a decolourant is not a strictly chronological progression, as the two technologies appear to overlap, and may perhaps represent regional differences in production practice. The two Near Eastern groups from Tel Anafa and Jebel Khalid follow the manganese decolourant practice, while the glass from all other sites included in this study were decoloured with antimony. Could these variations represent competing Syro-Palestinian and Aegean productions?

Examination of the data from all sites suggests that overall the Jebel Khalid and Tel Anafa glasses, although not exactly the same, are more similar to each other than to other groups, and the glasses from Rhodes are often distinct. While Tel Anafa and Jebel Khalid reduced glass composition and decolourant technology are closely similar, at Tel Anafa strongly coloured vessels form the majority of the assemblage [65: pp. 19–21], whereas this is not the case for the Jebel Khalid assemblage. Jennings [31: p. 56] concluded from comparison of Beirut and Tel Anafa bowls that although they were made in the same regional tradition, there were stylistic differences that suggested different secondary workshops, which could have been supplied with glass by a single primary location. Large numbers of bowls are recorded from Syro-Levantine sites suggesting a local coastal late Hellenistic glass industry which exported raw glass around the Mediterranean [30: pp. 26–27], as it had done since the Late Bronze Age [4]. Perhaps secondary production workshops in the Aegean using Syro-Palestinian produced glass could explain both the 'Greekness' of vessel forms and decoration observed at Jebel Khalid, and the greater similarity of Jebel Khalid with Tel Anafa glass compositions.

Decorative variation of chemically similar glass, as observed in the Jebel Khalid material, could also be explained by the production in one place of vessel blanks that were distributed to workshops where decoration was cut later. Alternatively, raw glass is known to have been distributed to workshops that both formed and decorated vessels. Both production models could have operated simultaneously alongside a third option where recycled cullet was collected at any number of locations and reworked into new vessels in a one-stop process. There are of course other possible variations on these production models, where different stages of the production of decorated vessels could have occurred in one or more locations.

The variations in composition between glass groups are subtle, but may suggest the possibility of more than one glassmaking centre in the eastern Mediterranean during the Hellenistic period: at least one in the Syro-Palestinian Levant, and one at Rhodes (see also [15: p. 96]). Shortland and Schroeder [55: pp. 962–963] also suggested that several primary production workshops in the eastern Mediterranean could have produced glass from imported Levantine sands. Although this remains unproven, we do know that raw and finished glass were both traded around the region (see also [10: p. 282]).

The picture of distribution networks is further extended by the possible trade in glass from further east of the Euphrates. From each of the sites of Pherai, the Rhodes Bead Factory and Rhodes Necropolis, Jebel Khalid and Tel Anafa are a small number of glasses that are outliers when magnesia and potash are plotted together (Fig. 5). Connolly et al. [15: p. 94] suggested that the high magnesia Pherai glasses could have been the imported products of the plant ash glassmaking tradition which survived through this period to the east of the Euphrates in Mesopotamia and Iran [24: p. 204, 37, 58: pp. 1284–1285].

When earlier Iron Age LMLK glass from Gordion and Assyrian Nimrud was compared with Hellenistic LMLK glass from sites in Greece and again from Gordion, differences that clearly indicated changes in glass chemistry through the course of the first millennium BCE were identified [45]. Were these changes the result of the establishment of new production sites, such as Rhodes, alongside traditional Levantine coastal centres, or did they rest on technological developments that evolved in the Levant and were shared amongst a widespread network of Mediterranean manufacturers?

Experimental

Quantitative analysis via electron microprobe

Fifty-nine samples of glass vessels, predominantly drinking bowls, were manually micro-sampled, resin-mounted, polished to <0.25 μm finish, evaporatively coated in ~25 nm carbon and analysed via wavelength dispersive spectrometry. Thirteen elements were analysed as oxides (oxygen content calculated by stoichiometry): Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, Sb_2O_3, FeO, CoO and CuO. Analyses were conducted at the University of New South Wales Electron Microscope Unit using a JEOL JXA-8500F electron microprobe (SEM-WDS). Operating conditions of 20 kV accelerating voltage, and 20 nA probe current were used for analysis. Observation of peak counts of potentially mobile elements (Na, K, Si) was undertaken to identify an optimal probe diameter of 30 μm for the analyses (i.e., no signal change during the duration of the analysis of these elements, no drop in signal due to beam defocusing). The system was calibrated using well-characterised natural and synthetic mineral standards. The quality of the results was checked via analysis of secondary standards, which were run at the beginning and end as well as intermittently between samples: Corning Museum of Glass standard reference glass B [9: pp. 539–544, 62] and Glen Spectra (UK) soda-lime-silica RM01. Detection limits were between 30 and 100 ppm for all elements

Table 3 Analytical data for reference glass samples corning B and RM01

Reference glass	Value	Na_2O	SiO_2	MnO	TiO_2	MgO	K_2O	FeO	CaO	Al_2O_3	P_2O_5	CoO	Sb_2O_3	CuO	Total
Corning B	Measured	16.83	61.74	0.25	0.11	1.01	1.11	0.34	8.52	4.08	0.82	0.04	0.48	2.51	97.84
	Stdev	0.27	0.39	0.01	0.01	0.01	0.04	0.01	0.05	0.06	0.03	0.01	0.02	0.10	
	Reported	17.00	61.55	0.25	0.09	1.03	1.00	0.31	8.56	4.36	0.82	0.05	0.41	2.66	98.09
RM01	Measured	13.21	72.49	0.00	0.03	3.95	0.31	0.04	8.53	0.57	0.01	0.00	0.03	0.00	99.17
	Stdev	0.26	0.41	0.01	0.01	0.03	0.02	0.01	0.04	0.02	0.01	0.00	0.01	0.00	
	Reported	13.50	72.40	–	–	3.99	0.30	–	8.49	0.61	–	–	–	–	99.29

Measured (this study) and reported data for corning B [9, 62] and RM01 (Glen Spectra, Stanmore UK); presented as measured average oxide weight percent (N = 24), one standard deviation of the measured values, and given oxide weight percent values analysed; analytical totals typically fell between 98 and 100 %. Upon examination of the few samples with totals falling below this range (via SEM and LA-ICP-MS), it is most likely that lower totals are reflective of the presence of additional, un-analysed elements. A number of samples were observed to exhibit porosity due to the presence of trapped gas bubbles, but analysis points were chosen to avoid apparent porosity as far as possible. Sample measurements were conducted in triplicate and averaged results are reported. Taking into account the values obtained from secondary standards and observed peak counts, analytical error is estimated to be better than 2 % relative for Na, Si, Mn, Mg, Ca and P oxides; ~5–10 % relative for remaining oxides in concentrations of 0.1–1 %, and up to 20 % relative for oxides at levels below 0.01 % concentration at the limits of detection. Results are reported in Table 1, including one standard deviation for each (triplicate) analysis. Analyses of reference glasses are presented in Table 3.

Conclusions

The translucent glass vessels of this study are consistent with and typical of 1st millennium BCE Hellenistic production in the eastern Mediterranean region. Vessel form, style, manufacture method and colour are independent of reduced glass composition. Glasses are decoloured with manganese, which also produced one purple glass. Blue is produced in one sample by cobalt with a little copper, and one green and one blue glass are coloured by copper. Other bluish and green glasses are the result of iron contamination in the batch. Amber glasses are likely the result of the presence of iron and sulphur in a ferri-sulphide complex.

Comparison of base glass compositions from around the Hellenistic eastern Mediterranean revealed a well-controlled product. While glass was made with similar batch ingredients in closely regulated proportions, minor variations are apparent, including the probable addition of plant ash, possibly from an eastern production. Two decolourant traditions were practiced, suggesting more than one primary production centre in the Aegean and the Levant. With little manufacturing evidence discovered so far, and limited comparative data, we cannot exclude the possibility of more than one glass production site that used well-controlled, comparable glass batch ingredients, and which engaged in active trade of raw and finished glass products. Vessel production could have occurred at many more secondary workshop sites in local styles, but general similarity of types and undoubted widespread trade make it difficult to distinguish geographical groups based on typology alone.

The earliest glass considered in this study from Vergina just precedes the Hellenistic period. The similarity of this glass to the later, extremely consistent Hellenistic glass compositions, suggests that this manufacturing tradition was already well established by the beginning of the Hellenistic era. Apart from the introduction of a new decolourant, glassmaking did not change during this period of nearly three centuries that set the stage for the consistency apparent in subsequent glass manufacture across the Roman Empire. We need to look back to pre-Hellenistic times for the development of this technology, and move forward to incorporate analysis of more comparative material, including vital trace element and isotope data to further investigate these questions.

Authors' contributions

WJR conceived of the study, participated in its design and coordination and drafted the manuscript. KLP participated in the study's design and coordination, conducted the analyses, and contributed to the manuscript. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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