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Hellenistic core formed glass from Epirus, Greece. A technological and provenance study

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A B S T R A C T

One of the earliest glassmaking techniques is the so-called core-forming technique. The earliest glass vessels made with this technique appeared in Mesopotamia and Egypt during the second half of the 2nd Millennium BC (16th–15th c. BCE). During the Iron Age the technique revived in Eastern Mediterranean and brought to light the largest numbers of glass vessels produced in the Mediterranean area in the 1st Millennium BCE, the so-called Mediterranean core formed bottles.

In the present study, an assemblage of 40 fragments of Hellenistic core formed vessels found in the most important Hellenistic sites of Epirus located in the north-west part of Greece is investigated by means of analytical techniques such as SEM/EDX and LA-ICP-MS. The main aim of this study is to identify the technology and the raw materials of the aforementioned glasses and try to answer provenance questions.

According to the study of major and minor elements that are associated with the source of silica, i.e. sand, it seems that in the Epirotic samples there is a choice of purer sands with less impurities compared to core-formed vessels dating to late archaic-classical periods (samples of the two consecutive core forming industries). This enforces the theory that the three core forming industries were independent, using different raw materials and therefore most likely they took place in totally different areas reinforcing the archaeological interpretations.

The majority of the Epirotic samples according to their trace element fingerprint present an Italian origin. Italy and especially south Italy (Magna Grecia) had long socio-economic, political and trade relations with Greece and especially Epirus during the reign of King Phyrrus. Furthermore, a small part of the Epirotic samples (samples from Cassope) have an Egyptian origin.

1. Introduction

Glass was one of the latest pyrotechnological products, which was invented by man. Glass existed in the form of beads and minor decorative objects since the 4th Millennium BCE. The earliest glass vessels appeared in Mesopotamia and in Egypt during the second half of the 2nd Millennium BCE (16th–15th c. BCE). These earliest glass vessels were manufactured with the core forming technique, which had begun in Western Asia and Egypt and was revived in Mesopotamia in the Early Iron Age.

The revival of the technique brought to light the largest numbers of glass vessels produced in the Mediterranean area during the 1st Millennium BCE, the so called Mediterranean core formed vessels, which were manufactured in three successive industries between the mid-6th c. BCE to the beginning of the 1st c. CE, termed as Mediterranean Group I (late 6th–mid-4th c. BCE), Group II (mid-4th–late 3rd c. BCE) and Group III (mid-2nd–early 1st c. CE) (Grose, 1989).

According to the current archaeological knowledge these vessels share a common function and technology and most of their forms imitate the shapes of Greek ceramic and metalware of the Archaic, Classical and Hellenistic periods. Primary production sites of these vessels have not been yet discovered, nevertheless various scholars have identified Rhodes, southern Italy and the Syro-Palestinian (or Syro-Cypriot) regions responsible for the production of Group I, II and III vessels respectively (Harden, 1981; McClelan, 1984; Grose, 1989). These vessels were circulated extensively all over the Mediterranean and were often offered as votives in sanctuaries and also served as perfume containers (Cosyns and Nys, 2010).

In the present study, an assemblage of core formed vessels, belonging mainly to Group II–III industry, found in the most important Hellenistic sites of Epirus in north-west part of Greece (Fig. 1) is investigated using state of the art analytical techniques. This study aims to answer technological questions and give new insights about the provenance of these samples broadening our knowledge in Hellenistic glassmaking.

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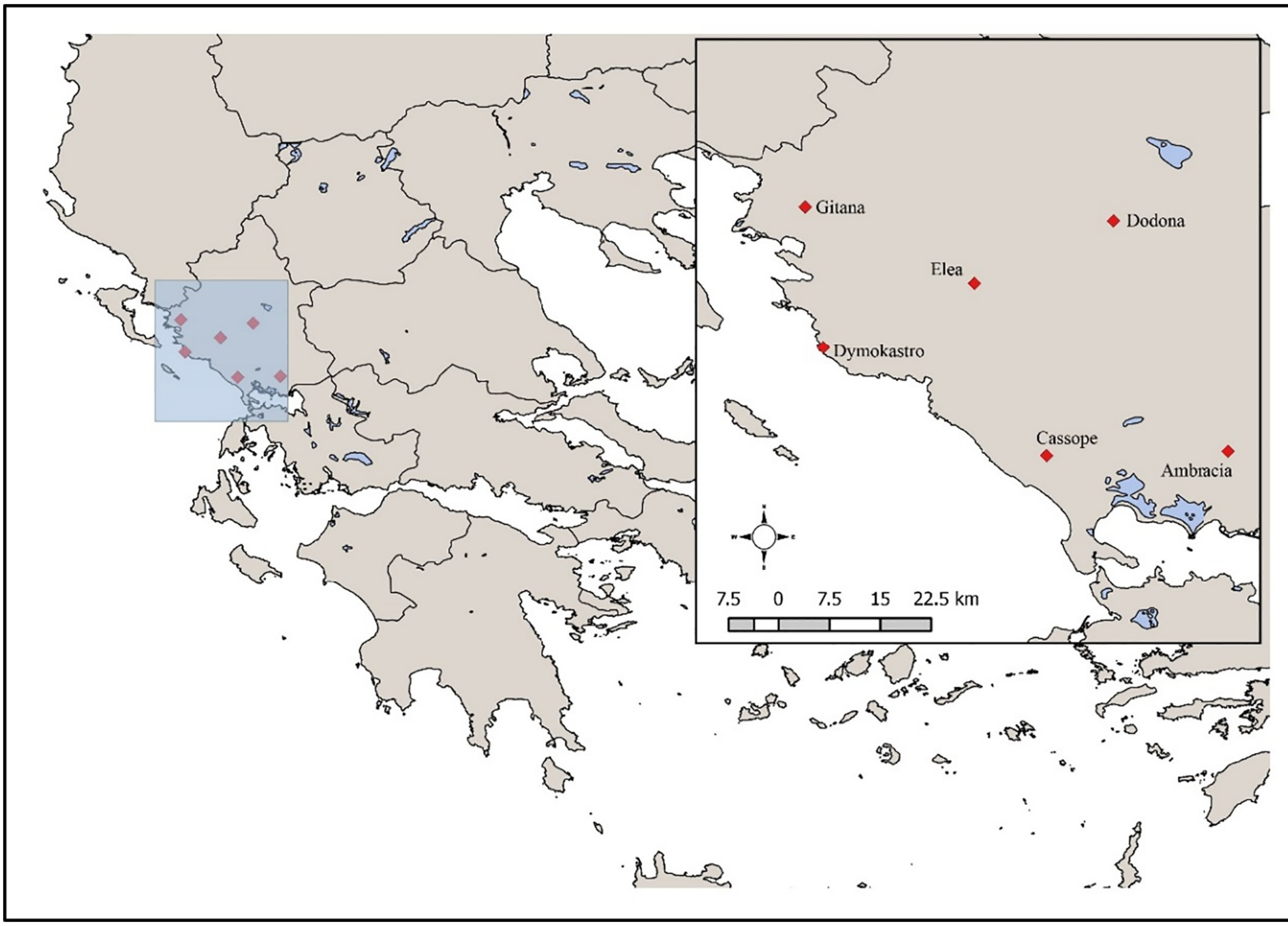

Fig. 1. Map of Epirus and the archaeological sites.

Ancient Epirus occupies the north-western part of Greece (Fig. 1) (Hammond, 1967; Sakellariou, 1997). During the Historical times (1st Millennium BCE) many colonies were founded in Epirotic region by the Eleans and the Corinthians (8th–7th c. BCE) and fundamental reforms occurred by King Tharipas (late 5th c. BCE) resulting in the gradual urbanization of the agro-kennel population (4th c. BCE). In Hellenistic times and especially during the reign of King Pyrrhus (297–272 BCE) (Lévêque, 1957; Katsikoudis, 2009) Epirus developed significantly (Franke, 1961; Liampi et al., 2013).

The brilliant development during the Hellenistic period was interrupted by the Roman destruction of Epirus in the early 2nd c. BCE (168–167 BCE) (Cabanes, 1976). The Epirotes after the extensive destruction gain again some privileges (coins, foundation of workshops, etc.) and no later than 155 BCE reunite in a single *Koinon* which function continued even after the 148 BCE (Palli et al., 2017). The picture in Epirus changes completely after the foundation of Nicopolis from Octovian August, in 30 BCE, in memory of his victory in Aktio (Chrysos, 1987; Zachos, 2007; Zachos et al., 2008).

In Epirus, during the Hellenistic period, the sanctuary of Dodona is developing and magnificent cities like Ambracia in the urban network of modern Arta, Cassope in ancient Cassopaea (Dakaris, 1971) and Elea, Gitana and Dymokastro in ancient Thesprotia (Dakaris, 1972) are founded. The samples under study were excavated at these important archaeological sites.

2. Materials and methods

2.1. Materials

In this study 40 fragments of core formed glass vessels (Fig. 2) were investigated with SEM/EDX and LA-ICP-MS analytical techniques. According to the typological characteristics the majority of samples ($n = 15$) belong to the Mediterranean Group II–III category, while there are five samples belonging to Mediterranean Group I category (Grose, 1989; Stern and Schlick-Nolte, 1994). The rest of the fragments ($n = 20$) are non-diagnostic therefore the presumed category, i.e. Group II-III, is established in terms of their archaeological context which is connected to mid Hellenistic (230–150 BCE) and late Hellenistic (150–30 BCE) period (Table 1). Typologically the samples are distinguished in three broad categories alabastra, amphoriskoi and unguentarium while there are few fragments that are not diagnostic (Table 1). The samples have a typical dark opaque blue colour bearing decorative threads mainly of white and yellow opaque colour.

2.2. Sample preparation

All samples were cleaned meticulously with acetone and in an ultrasound bath with distilled water. A small fragment (1–2 mm) was removed from all samples, mounted in resin blocks and grinded with silicon carbide papers of various grits (800, 1200, 2500 and 4000 grits). Finally, the samples were polished with diamond paste of 3–6 μm and 1 μm.

Fig. 2. Characteristic fragments of the core formed vessels found in the archaeological sites of Epirus.

2.3. Scanning electron microscopy (SEM)

A SEM facility at the Laboratory of Archaeometry, University of Peloponnese, Kalamata, Greece was used to identify the major and minor elements. The JEOL (JSM-6510LV) Scanning Electron Microscope is equipped with an Energy Dispersive X-ray Spectrometer Oxford Instruments. Due to submicrometer beam size, 5 analyses of 300 s were performed on each sample and the mean value was calculated for each element. The accuracy and precision of the technique is shown in Table 2 (Oikonomou et al., 2016).

2.4. Laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS)

The LA-ICP-MS facility at the Centre for Environmental Geochemistry, at the British Geological Survey, Keyworth, UK was used to identify the trace elements. The ablation was conducted with a NewWave UP193FX excimer (193 nm) laser system, with built in microscope imaging, which was coupled to an Agilent 7500 series ICP-MS. Laser ablation craters were set at 70 µm and 3 measurements of 45 s each were performed on every sample. To test the accuracy and precision of the facility NIST 612 reference material was used and the results are shown on Table 3.

3. Results and discussion

3.1. Introduction

Glassmaking involved various stages (e.g. sourcing and processing of raw materials, gathering fuel, construction of a high temperature installation, fusing the raw materials, formatting and decorating the final object, etc.) (Oppenheim et al., 1970; Henderson, 2000; Shortland, 2012). Usually glass is made by mixing two main raw materials/components (Brill, 1988): the source of silica and the source of alkali, which for Hellenistic period is sand and natron respectively (Henderson, 2013). This leads to the manufacture of a base glass, which had very specific visual characteristics (usually a semi-transparent/translucent glass having a greenish hue). Ancient glassmakers, in order to achieve specific aesthetic results such as colour and opacity, were trying to modify the base glass composition either in the primary stage (mixing of the main raw materials) or in a secondary stage (remelting or recycling) by adding to the glass batch secondary components such as colorants, decolorants and opacifiers.

Elements that can be associated with the sand source are SiO_2 (the main component of sand) and Al_2O_3, Fe_2O_3 and CaO (the main impurities of sand). Trace elements that can be associated with sands, such as Ti, Cr, La, Zr, Ba, Sr, Li, Rb, Y, Nd and Hf, are connected to various minerals in rocks or sediments which are found as accessory minerals in sands (Brems and Degryse, 2014b). The correlations between these elements have provided useful information about technology and provenance of glass of specific regions and dates (Freestone et al., 2000; Paynter, 2006; Shortland et al., 2007; Silvestri, 2008; Silvestri et al., 2008; Walton et al., 2009; Polikreti et al., 2011; Henderson et al., 2016; Oikonomou et al., 2016; Blomme et al., 2017).

3.2. Results

The core formed vessels from Epirus have a typical glass composition for the Hellenistic period (Table 4). All samples fall into the broad category of soda-silica-lime glass composition (Sayre and Smith, 1961). The main glass former of the samples is silica (SiO_2) ranging from 58.75% wt. to 73.63% wt. with the mean value of 70.31% wt., while the main alkali, used to lower the melting point of silica, is sodium oxide (Na_2O) which has concentrations between 13.75% wt. and 21.72% wt. with an average value of 17.60% wt. A secondary alkali component detected in the samples is potassium oxide (K_2O), which is found in much lower values, ranging from 0.23% wt. to 1.36% wt. with an average of 0.69% wt. The alkali earth components discovered in the glass samples are calcium oxide (CaO) and magnesium oxide (MgO), which are found in levels of 6.06% wt. and 0.63% wt. respectively. Finally, two more oxides were detected, alumina (Al_2O_3) and iron oxide (Fe_2O_3), in levels of 2.22% wt. and 0.61% wt. respectively.

Table 1

The typology of the glass finds under study and information regarding the archaeological context. The archaeological context dates to mid Hellenistic (230–150 BCE) and late Hellenistic (150–30 BCE) period. *The assignment of the non-diagnostic (n.diag) fragments to Group II–III category is based on the dating of the archaeological context.

Region	Sample	Archaeological context	Typology	Group
Dodona (Dakaris, 1965, 1983)	Do3	Public building, Extension of the Prytaneion	Amphoriskos	I
	Do5	Public building, Extension of the Prytaneion	Amphoriskos	I
	Do6	Between the public building of Bouleutirion and the Hellenistic temple of Aphrodite	Alabastron	II
	Do7	Between the public building of Bouleutirion and the Hellenistic temple of Aphrodite	Alabastron	II
	Do8	Between the public building of Bouleutirion and the Hellenistic temple of Aphrodite	Unguentarium	II–III
Ambracia CE 1995 (Aggeli, 2000)	Ar13a	West cemetery of Ambracia, Theodorou plot	Alabastron	I
	Ar13b	West cemetery of Ambracia, Theodorou plot	Alabastron	I
	Ar36a	West cemetery of Ambracia, Kommenou street	Alabastron	II
	Ar36b	West cemetery of Ambracia, Kommenou street	Alabastron	II
Cassope (Hoepfner and Schwandner, 1994)	Cas1	House 5, city of Cassope	n.diag.	II–III*
	Cas2	House 2, city of Cassope	n.diag.	II–III*
	Cas3	House 2, city of Cassope	Alabastron	II–III
	Cas4	House 2, city of Cassope	n.diag.	II–III*
	Cas5	House 2, city of Cassope	Alabastron	II–III
	Cas6	House 2, city of Cassope	Amphoriskos	I
	Cas20	House 4, city of Cassope	n.diag.	II–III*
Elea	El2	House or workshop (at least few places of the building has a workshop activity)	n.diag.	II–III*
(Riginos and Lazari, 2008)	El3	House or workshop (at least few places of the building has a workshop activity)	n.diag.	II–III*
Dymokastro (Lazari et al., 2008)	Dy1	Acropolis A, Section B, surface find	n.diag.	II–III*
	Dy19	Acropolis A, Building B, Private house with a water cistern	n.diag.	II–III*
	Dy20	Acropolis A, Building B, Private house with a water cistern	n.diag.	II–III*
	Dy38	Acropolis B, Building 3, sanctuary	n.diag.	II–III*
	Dy39	Acropolis B, Building 3, sanctuary	n.diag.	II–III*
	Dy40	Acropolis B, Building 3, sanctuary	n.diag.	II–III*
	Dy41	Acropolis B, Building 3, sanctuary	n.diag.	II–III*
	Dy42	Acropolis B, Building 3, sanctuary	Unguentarium	II–III
	Dy43	Acropolis B, Building 3, sanctuary	Alabastron	II–III
	Dy44	Acropolis B, Building 3, sanctuary	Alabastron	II–III
	Dy45	Acropolis B, Building 1, private house	n.diag.	II–III*
Gitana	Gt1a	Section 9, layer B	Alabastron	II–III*
	Gt1b	Section 9, layer B	Alabastron	III
	Gt2	Inside the settlement, Building 31, possible workshop	Alabastron	II
	Gt3	Section 32, layer B	Alabastron	II–III*
	Gt4	Inside the settlement, Road 6, west of small temple	n.diag.	II–III*
	Gt5	Inside the settlement, Road 12, west side	Alabastron	II–III
	Gt19	Section 67, layer B	n.diag.	II–III*
	Gt20	Section 80, layer B	n.diag.	II–III*
	Gt21	Inside the settlement, Road 12, north of Road 6	Alabastron	II
	Gt22	Inside the settlement, junction between Road 13 and Road 6	n.diag.	II–III*
	Gt23	Inside the settlement, junction between Road 13 and Road 6	n.diag.	II–III*

Table 2

Measured and expected values of major and minor oxides for the NIST 620, 1831 and 612 standard reference materials (SRM) (in % wt.). The expected values for SRM612 were provided by GeoRem (Jochum et al., 2011).

SAMPLE	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO
620	14.19	3.66	1.72	73.59	0.21	0.39	6.27
Expected	14.39	3.69	1.8	72.08	0.28	0.41	7.11
1831	13.67	3.67	1.20	74.03	0.27	0.29	6.9
Expected	13.32	3.51	1.21	73.08	0.25	0.33	8.2
612	13.94	–	2.06	72.93	–	–	11.08
Expected	13.7	–	2.03	72.1	–	–	11.9

3.3. Discussion

The analytical data provided by the techniques show interesting correlations in terms of the major minor and trace elements composition of the core formed glass from Epirus.

3.3.1. Sand

In the present study, the mean values of Al_2O_3 and Fe_2O_3 are very close to the typical concentrations found in sands, and which are not expected to change significantly in the final product (chemical composition of sands can be found in Brill, 1988, 1999 and Degryse, 2014), indicating sand as the source of SiO_2.

Potential correlation between the oxides SiO_2, Al_2O_3, Fe_2O_3 and CaO might reveal possible different sand sources as it has demonstrated in previous works (indicatively see: Mirti et al., 2009; Schibille, 2011; Gallo et al., 2013; Gallo et al., 2014; Freestone and Jackson-Tal, 2015; Freestone and Stapleton, 2015; Oikonomou et al., 2016). In this paper, the correlation between SiO_2 and the sum of the other three oxides, which are, in most cases, introduced with the same raw material i.e. sand, is shown in Fig. 3. On the same plot data from published works are also presented. The analytical data of core formed vessels Group III

Table 3

Measured and expected values of trace elements for the NIST 612 standard reference material (SRM) (in ppm). The expected values were provided by GeoRem (Jochum et al., 2011).

Sample	Li	Ti	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Sn	Ba	La	Nd	Hf
NIST 612	40.9	45.0	36.3	37.9	34.8	38.7	37.5	40.2	34.1	31.6	79.0	37.8	37.4	44.5	39.1	35.7	35.3	36.0
Expected	40.2	44	36.4	38.7	35.5	38.8	37.8	39.1	35.7	31.4	78.4	38.3	37.9	38.6	39.3	36	35.5	36.7

Table 4
The analytical data from the SEM/EDX and LA-ICP-MS analyses of the 40 samples (n.m.: not measured, s.d.: standard deviation).

		SEM/EDX Analysis (in % wt.)									LA-ICP-MS Analysis (in ppm)																	
Region	Sample	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	Fe_2O_3	Li	Ti	Cr	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Sn	Ba	La	Nd	Hf
Dodona	Do3	15.14	0.41	2.10	71.75	0.42	1.15	0.63	7.75	0.65	3.4	319	6.9	117	170	4	817	39	4	11	485	7.1	38	13	215	6.1	6.3	0.8
	Do5	15.01	0.44	2.22	72.21	0.31	1.18	0.56	7.39	0.69	2.9	299	6.2	105	191	4	551	30	2	10	496	8.6	45	11	212	6.7	6.8	0.9
	Do6	14.37	0.44	2.10	72.25	0.26	1.32	0.46	7.71	1.09	3.0	344	7.0	102	292	5	873	222	5	8	475	9.1	39	27	200	6.7	6.4	1.1
	Do7	15.57	0.89	2.52	67.92	0.35	1.13	0.99	9.09	0.66	5.2	710	14.2	6787	40	12	3953	24	9	12	493	8.9	58	18	261	7.6	7.4	1.5
	Do8	15.98	0.31	2.53	71.71	0.01	1.69	0.36	6.56	0.83	3.1	315	6.5	92	1531	6	716	276	6	7	445	7.4	31	18	196	6.1	5.9	0.8
Ambracia	Ar13a	18.14	0.54	2.32	71.63	0.23	0.85	0.71	5.20	0.37	4.9	321	9.3	1213	813	36	1428	36	11	12	451	6.3	33	54	227	6.0	6.0	0.9
	Ar13b	16.81	0.63	2.65	71.75	0.24	0.89	0.84	5.64	0.55	3.9	345	9.6	1666	1162	55	1567	50	18	15	458	6.3	33	72	221	5.9	5.7	0.8
	Ar36a	13.83	0.52	2.18	71.00	0.50	0.89	1.36	7.86	1.19	4.2	391	8.8	4035	1027	44	5890	108	34	13	465	7.0	38	63	231	6.0	5.9	0.9
	Ar36b	13.75	0.61	2.22	71.06	0.56	0.93	1.27	7.71	0.92	3.8	443	9.8	3631	934	39	4416	70	32	13	496	8.7	47	88	244	7.2	7.0	1.1
Cassope	Cas1	20.46	0.70	2.31	70.68	0.29	0.77	0.50	4.01	0.19	3.3	304	7.4	1631	872	37	973	34	11	10	441	6.1	33	57	212	5.6	5.9	0.8
	Cas2	17.83	0.50	2.04	70.77	0.33	0.94	0.34	6.58	0.68	2.5	311	7.9	103	1458	9	1449	151	6	7	496	7.0	30	9	186	6.2	6.2	0.7
	Cas3	18.32	0.57	1.80	68.89	0.42	0.99	0.52	6.91	0.86	7.6	685	11.0	1592	1235	85	4875	115	14	8	309	5.2	102	296	164	6.9	6.5	2.5
	Cas4	16.76	0.61	1.18	73.04	0.32	1.13	0.23	5.64	0.59	4.9	802	10.5	2016	1073	77	989	66	4	4	230	5.0	73	38	117	6.6	6.4	1.8
	Cas5	19.22	0.63	1.53	69.70	0.40	0.89	0.45	6.40	0.76	8.1	683	10.6	1829	1392	93	4762	116	14	8	306	5.4	99	351	166	7.0	6.8	2.4
	Cas6	19.72	0.80	2.24	68.43	0.15	0.90	0.84	5.88	0.44	4.1	400	9.2	6796	442	14	557	31	10	14	576	6.7	34	244	237	6.1	6.0	0.9
	Cas20	17.25	0.90	1.50	73.63	0.34	1.07	0.57	3.33	1.40	5.2	1367	15.0	3369	1314	118	3762	326	47	4	215	5.4	134	56	171	7.1	6.2	3.3
Elea	El2	18.05	0.70	2.34	71.42	0.25	0.88	0.64	5.19	0.53	3.1	328	7.5	611	783	31	1707	71	17	10	428	5.5	27	38	215	5.4	5.4	0.7
	El3	16.64	0.69	2.23	72.40	0.12	0.90	0.67	5.77	0.58	3.1	332	7.9	846	1100	42	2823	77	24	10	446	6.7	34	51	214	5.8	6.3	1.0
Dymokastro	Dy1	17.86	0.63	2.28	70.75	0.27	0.92	0.74	6.07	0.46	4.9	463	14.4	15,497	345	40	3704	87	19	11	735	7.4	40	557	426	7.3	6.7	1.1
	Dy19	20.16	1.02	2.64	69.69	0.18	0.67	1.07	4.25	0.32	4.4	436	14.6	5850	763	45	3276	128	36	12	516	7.5	38	71	260	6.6	6.2	1.0
	Dy20	18.40	0.65	2.34	66.90	0.36	1.05	0.69	7.49	0.80	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
	Dy38	17.22	0.51	2.26	72.96	0.29	0.79	0.49	5.25	0.28	3.0	328	7.9	1231	898	27	1190	45	12	10	460	6.5	35	18	206	5.8	6.0	0.9
	Dy39	16.55	0.54	2.30	72.41	0.12	1.04	0.58	6.12	0.34	3.0	326	8.1	146	198	8	1377	115	9	9	431	7.1	35	8	233	5.8	6.0	1.0
	Dy40	17.90	0.40	2.17	69.35	0.48	1.13	0.73	6.50	0.38	3.7	290	6.8	6353	1567	79	1302	51	12	10	562	7.7	35	58	236	5.9	5.9	0.9
	Dy41	18.48	0.44	2.00	68.95	0.28	1.36	0.66	6.68	0.45	3.4	281	6.5	6277	1577	77	1397	51	12	10	552	7.4	35	56	238	6.0	6.1	0.8
	Dy42	18.84	0.83	2.41	68.03	0.28	0.59	0.96	6.70	0.46	4.3	486	13.7	13,233	1707	66	2560	54	16	12	675	7.8	44	111	389	7.1	7.0	1.0
	Dy43	16.22	0.43	2.32	72.65	0.24	0.94	0.73	5.92	0.54	3.4	371	8.2	147	437	15	1631	204	30	13	447	7.2	37	15	222	6.2	6.2	0.9
	Dy44	16.71	0.58	2.22	71.53	0.34	0.87	0.75	6.64	0.40	3.2	351	7.6	963	1048	46	1273	34	12	10	466	7.1	36	53	206	5.9	5.8	1.0
	Dy45	16.25	0.59	2.29	72.54	0.32	0.96	0.55	5.97	0.60	3.2	410	8.3	158	737	15	2019	278	21	9	438	7.6	41	20	222	6.6	6.4	1.1
Gitana	Gt1a	18.98	0.84	2.22	69.20	0.26	0.85	1.11	5.75	0.31	5.1	383	9.7	6954	448	22	1209	42	9	12	557	7.1	35	30	232	6.1	6.2	0.9
	Gt1b	18.06	0.97	1.88	72.15	0.18	0.48	0.61	3.87	0.17	5.4	418	10.6	6990	444	24	3295	47	12	13	576	7.3	37	29	238	6.7	6.4	0.9
	Gt2	18.24	0.55	2.21	69.29	0.45	1.00	0.81	5.92	0.58	3.6	363	9.0	9373	282	21	998	35	13	13	529	5.7	33	107	246	5.6	5.6	0.7
	Gt3	19.60	0.58	2.27	68.10	0.49	0.66	0.65	5.67	1.97	4.2	369	12.2	667	885	23	3328	152	10	11	407	7.2	34	10	201	6.4	6.3	0.8
	Gt4	19.40	0.71	2.48	70.19	0.24	0.80	0.60	5.29	0.29	2.9	348	8.4	2089	952	30	1780	50	15	9	445	6.7	34	34	228	5.8	5.7	0.8
	Gt5	18.33	0.65	2.33	69.06	0.24	1.12	0.74	6.98	0.54	4.0	431	18.9	2169	281	15	603	32	11	10	445	6.8	41	17	225	6.1	5.9	1.1
	Gt19	18.87	0.89	2.24	69.03	0.29	0.78	0.93	6.02	0.42	4.5	428	9.6	8166	426	17	480	32	9	15	580	7.1	36	196	244	6.1	5.9	0.9
	Gt20	17.25	0.57	2.37	69.71	0.39	1.08	0.54	6.55	0.79	5.4	492	10.3	7207	1091	128	4322	157	26	9	467	7.1	41	135	259	6.2	6.3	1.1
	Gt21	17.95	0.35	2.21	70.75	0.48	0.68	0.56	5.61	0.68	2.3	303	7.0	7863	1423	46	1655	20	14	9	425	6.1	31	43	832	5.4	5.4	0.8
	Gt22	18.15	0.63	2.36	70.20	0.35	0.72	0.77	5.89	0.61	3.3	354	8.1	3518	2082	65	3138	20	19	11	422	7.4	44	134	454	6.0	5.9	1.1
	Gt23	21.72	1.01	2.84	58.75	0.65	n.m.	0.58	2.67	0.08	4.7	549	13.0	3194	697	26	2172	293	44	9	506	9.0	54	115	217	7.8	7.3	1.5
	Average	17.60	0.63	2.22	70.31	0.32	0.95	0.69	6.06	0.61	4	433	10	3707	875	40	2175	97	16	10	471	7	44	85	249	6	6	1
	s.d.	1.77	0.18	0.31	2.50	0.13	0.22	0.24	1.27	0.35	1	197	3	3785	501	31	1436	84	11	2	99	1	22	110	115	1	0	1
	Max	21.72	1.02	2.84	73.63	0.65	1.69	1.36	9.09	1.97	8	1367	19	15,497	2082	128	5890	326	47	15	735	9	134	557	832	8	7	3
	Min	13.75	0.31	1.18	58.75	0.01	0.48	0.23	2.67	0.08	2	281	6	92	40	4	480	20	2	4	215	5	27	8	117	5	5	1

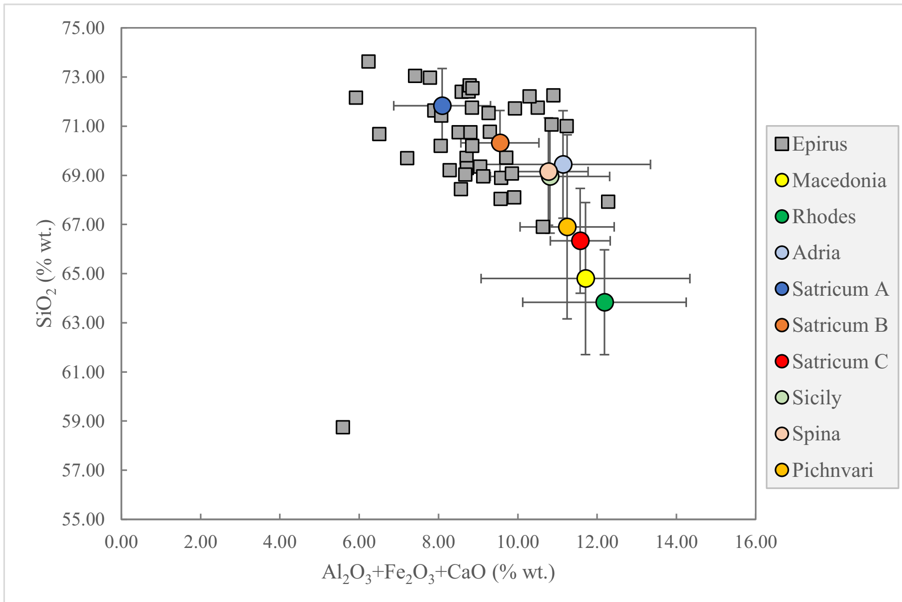

Fig. 3. Correlation between SiO_2 and Al_2O_3 + Fe_2O_3 + CaO for the Epirotic samples. The mean values and standard deviations (crosses) of published data of core formed vessels are also shown. The samples have the tendency to correlate negatively.

Table 5
Mean values and standard deviations of published data for Group I (late 6th - mid-4th c. BC), Group II (mid-4th - late 3rd c. BC) and Group III (mid-2nd - early 1st c. AD) glass for specific major and minor elements.

Location	Dating (Group)	SiO_2 (% wt.)	Al_2O_3 + Fe_2O_3 + CaO (% wt.)	K_2O (% wt.)	MgO (% wt.)
Macedonia, Greece (Blomme et al., 2017)	I, II	65.4 ± 4.5	11.1 ± 2.7	0.6 ± 0.3	0.6 ± 0.1
Rhodes, Greece (Triantafyllidis et al., 2012)	I, II	63.8 ± 2.1	12.2 ± 2.1	0.9 ± 0.5	0.7 ± 0.1
Adria, Italy (Panighello et al., 2012)	I, II, III	69.4 ± 2.2	11.1 ± 2.2	0.7 ± 0.4	0.6 ± 0.2
Satricum Italy (Oikonomou et al., 2016)	A. (II)	71.8 ± 1.5	8.1 ± 1.2	0.31 ± 0.05	0.58 ± 0.05
	B. (II)	70.3 ± 1.3	9.6 ± 1.0	0.49 ± 0.08	0.6 ± 0.1
	C. (II)	66.3 ± 0.9	11.6 ± 0.8	0.46 ± 0.09	0.6 ± 0.1
Sicily, Italy (Arletti et al., 2012)	I, II, III	68.9 ± 2.3	10.8 ± 1.5	0.5 ± 0.1	0.6 ± 0.2
Spina, Italy (Arletti et al., 2011)	I, II, III	69.2 ± 2.2	10.8 ± 1.0	0.6 ± 0.1	0.5 ± 0.1
Pichnvari, Georgia (Shortland and Schroeder, 2009)	I, II	66.9 ± 3.7	11.2 ± 1.2	0.52 ± 0.09	0.6 ± 0.2

are very scarce in the literature and therefore the comparison is made with samples dated in earlier periods, from the preceding core formed industries, namely Mediterranean Group I and II (Pichvnari, Georgia: Shortland and Schroeder, 2009; Spina, Italy: Arletti et al., 2011; Sicily, Italy: Arletti et al., 2012; Adria, Italy: Panighello et al., 2012; Rhodes, Greece: Triantafyllidis et al., 2012; Satricum, Italy: Oikonomou et al., 2016; Macedonia, Greece: Blomme et al., 2017). For clarity reasons, the published data are presented with their mean values and their standard deviations, which are also shown in Table 5.

According to Fig. 3 useful information can be derived. The majority of the Epirotic samples cluster in the upper left part of the plot in good correlation with the Satricum A and B samples (slightly better with Satricum B samples) having rather higher amount of SiO_2 and lower amount of the sum of Al_2O_3 + Fe_2O_3 + CaO. It is interesting to notice that the majority of the other samples present the exact opposite behavior: they have lower SiO_2 content and rather higher Al_2O_3 + Fe_2O_3 + CaO content.

It seems that part of the earlier glasses (samples from Adria, Spina and Sicily) are manufactured in the same production center, or at least using very similar raw materials. It is also interesting to note that all samples (this study and the published data) belonging to Group I, II and III categories of core formed vessels are correlated with a negative slope. The negative slope is compatible with the scenario that includes the interchange of compositionally differing sand sources. It can be assumed that the earlier samples (e.g. Pichvnari, Rhodes, Macedonia) use sand source(s) having more impurities (or more calcareous sands) while the later samples (e.g. Epirus, Satricum A and B) use more pure sand(s).

According to certain scholars the three succeeding industries of the Mediterranean core formed vessels happened to specific places and were not wide spread as later glassmaking industries e.g. glassmaking during Roman period when the scale of glass production increased enormously with glass products becoming a widespread and affordable commodity (Blomme et al., 2017). According to the scholars Rhodes, Magna Grecia and/or Macedonia and Cyprus and/or the Syro-Palestine coast have been suggested as glassmaking centers of the core formed vessels of Group I, II and III industries respectively (Harden, 1981; McClelan, 1984; Grose, 1989; Stern and Schlick-Nolte, 1994; Triantafyllidis, 2003; Cosyns and Nys, 2010).

This means that the supply of raw materials and the glass workshops, especially the ones specialized in core forming technique, were limited leading to the assumption that this correlation shown on Fig. 3 might serve as a compositional and dating marker; the earlier samples are plotted in the lower place of the trend line (more impurities less silica content of the sand) and the later ones on the top of the trend line (less impurities more silica content). It seems that there is an obvious change in the compositional characteristics of the three core forming industries (Group I, II and III), which reinforces the archaeological interpretation that these industries happened in different geographical places.

In addition, the data of 11 trace elements, which were detected in the glass samples from the 6 Epirotic sites, as well as published data

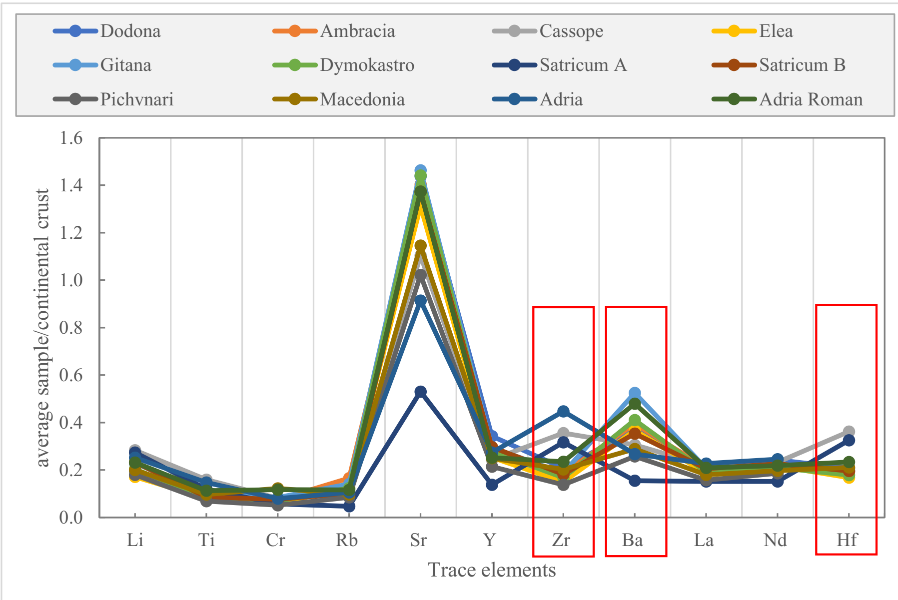

Fig. 4. The trace element signature of Epirotic samples compared to other published data. Most of the samples show similar behavior, but samples from Cassope, Satricum A and Adria show variation in their Zr, Ba and Hf content (red rectangulars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from Satricum and Adria in Italy, Macedonia in Greece and Pichvnari in Georgia, were used for comparison reasons and are plotted on Fig. 4. The values of these trace elements are normalized with the average composition of earth's continental crust in order to provide better and easier comparison among the different regions. In this paper, the average continental crust values provided by Wedepohl (1995) are used.

The compositional profiles of these samples show a consistency, but few exceptions can be noticed. In particular, while the majority of the trace elements of all regions have similar average values, there are three elements Zr, Ba and Hf (red rectangulars, Fig. 4), which have the biggest variation among the regions. More specifically, the samples coming from Cassope can be easily distinguished from the rest, having higher Zr and Hf and lower Ba values.

Zr and Hf are two elements associated to each other and are accumulated in the heavy mineral zircon (Brems and Degryse, 2014b). Ba on the other hand is related to alkali feldspar (Brems and Degryse, 2014b) or to barite ($BaSO_4$), which is found as concretions in sands and sandstones and is the likely main mineral in sands (Oikonomou et al., 2016). It is interesting to note that the same behavior is also noticed at the Satricum A and Adria samples (with the exception of Hf for Adria samples because of the lack of analytical data). For these samples excavated in Italy an alternative origin has been suggested by Arletti et al. (2011) and Oikonomou et al. (2016) respectively. In particular, there are strong indications that these samples have an Egyptian origin. We therefore can assume that the samples from Cassope have the same provenance or/and were manufactured with the same raw materials.

An interesting correlation can be shown in Fig. 5 where the ratios of Zr/Hf and Ti/Nd are plotted. According to the graph there are two distinct groups of samples, group A having lower Ti/Nd values (less than 80) and group B having elevated values of Ti/Nd (more than 90). Ti is generally related to the heavy mineral fraction in the sand raw materials such as rutile (TiO_2), ilmenite ($FeTiO_3$) and titanite ($CaTiSiO_5$), while Nd is presumed to be related to accessory minerals such as zircon present in sands (Brems and Degryse, 2014a). These ratios can therefore be possible independent markers for differentiating sand sources used to make glasses.

This distinction can be related to the use of different sands in the manufacture of these artefacts. It is interesting to note that among the samples from Epirus four out of seven from Cassope and one out of five from Dodona show high Ti/Nd content while the rest have low Ti/Nd content. This differentiation between the samples of the same site reflects supplies from different glassmaking sites. While this is somehow expected for the Dodona samples, since Dodona is a sanctuary and pilgrims and worshippers from around the Greek region and beyond were visiting the sanctuary, for Cassope, on the other hand, is unexpected and highlights the importance of the city and the different economical-trade activities that took place during the Hellenistic period. The majority of Epirotic samples have lower values of Ti/Nd and seem to correlate with the samples from Macedonia and Satricum B. Furthermore, Satricum B and Macedonia samples have two different provenances (Italy and Syro-Palestine) according to Oikonomou et al. (2016) and Blomme et al. (2017), which makes the identification of the origin of Epirotic samples more complicated. Nevertheless, in Fig. 3 there is a clear distinction between the Epirotic samples and the samples from Macedonia while there is a better correlation with the Satricum B samples. This last correlation is better shown in a SiO_2-Al_2O_3 biplot (Fig. 6) where the SiO_2 and Al_2O_3 content of Epirotic samples is very similar to Satricum B while the Macedonia samples have far less SiO_2. On top of that, one should take into consideration the socio-economic and cultural connections that ancient Epirus had with Italy and especially south Italy (Soueref, 2014) and of course the close proximity by sea to the Italian peninsula leading to the assumption that Epirotic samples and Satricum B might share the same origin.

The other 5 Epirotic samples with the higher ratio of Ti/Nd correlate clearly with Satricum A which according to Oikonomou et al. (2016) have an Egyptian origin. The socio-economic contacts between Epirus and Egypt is well attested both historically and archaeologically. Especially since the early 3rd c. B.C. Epirus developed close relations with the Ptolemaic Kingdom of Egypt and King Pyrrhus had political and social connections with King Ptolemy I which illustrates the communication channels between Epirus and Egypt during the Hellenistic period (Kondis, 1992; Soueref, 2014).

3.3.2. Natron

According to Fig. 7 all samples cluster in the area of low MgO low K_2O. It is interesting to note that most of the samples cluster in the middle of the graph and are correlated very well with the core formed samples of the other regions showing possible common origin of natron raw material. Only the samples from Rhodes show slightly elevated values of both oxides. There are also few samples (n = 10) that do not fit in the general picture of the majority of Epirotic samples and are clearly distinguished having slightly elevated values on both oxides.

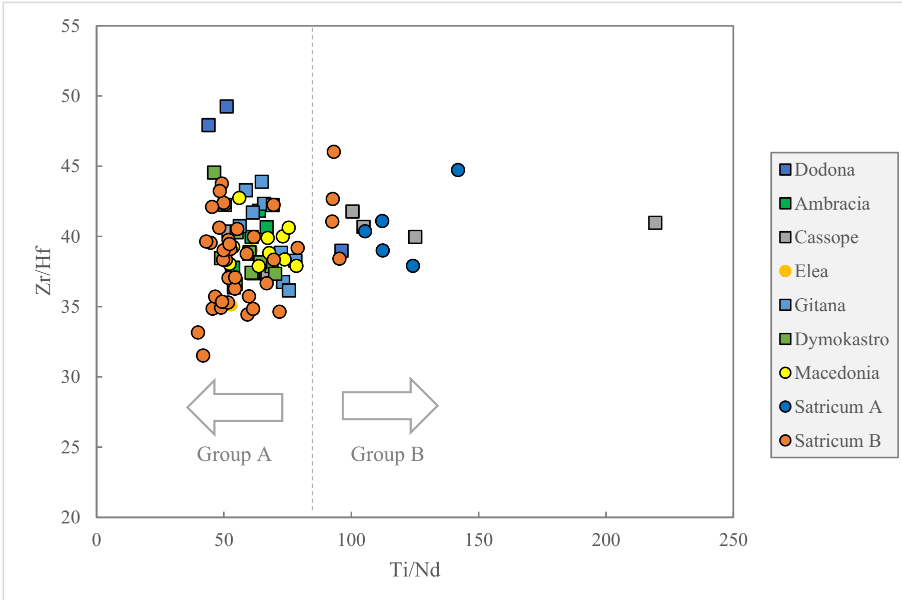

Fig. 5. Correlation between the Zr/Hf and Ti/Nd ratios of the Epirotic samples and the published data. There are two main groups of samples, one (the majority of samples) having Ti/Nd ratio less than 80 and the second having Ti/Nd ratio more than 90 indicating possible different source of sands.

3.3.3. *Colorants*

The samples under study exhibit the typical deep blue opaque colour. The Sb detected in the samples of each site averages in 1681 ppm for Dodona samples, 1159 for Ambracia samples, 672 ppm for Cassope samples, 260 ppm for Elea samples, 705 ppm for Dymokastro samples and 3194 ppm for Gitana samples. As expected the coloration is due to the simultaneous presence of both cobalt (Co) and copper (Cu) (mean values: 875 and 2175 ppm respectively) belonging to a CoCu colouring category (Shortland and Eremin, 2006; Shortland et al., 2007; Smirniou and Rehren, 2013). Some of the samples which exhibit slightly elevated amounts of Cu have at the same time considerable amounts of Sn suggesting the use of bronze or bronze scrap noticed by various scholars (Turner, 1956; Kaczmarczyk and Hedges, 1983; Brill, 1992; Shortland, 2000; Shortland, 2012; Henderson, 2013). Copper most likely was introduced in the glass in an effort to control the hue of the blue colour (deepen it as possible) and was incorporated in the glass with deliberate addition of a copper metal or ore without of course excluding possible mixing of cobalt and copper coloured glasses (recycling or in purpose mixing of different hue glasses) (Shortland and Eremin, 2006; Shortland, 2012; Oikonomou et al., 2012). Cobalt and copper do not seem to correlate strongly but we can notice a rough clustering and the samples can be distinguished in 3 main groups marked with rectangulars in Fig. 8 indicating possible different sources of Co or this distinction possibly, but less likely, due to the high variability in various elements of the cobalt ores.

Cobalt can be associated with various minerals such as cobaltite (CoAsS), absolane (a mixture of MnO and CoOOH), trianite ($2Co_2O{\cdot}CuO{\cdot}6H_2O$) and skutterudite ($(Co,Ni,Fe)As_3$) and with

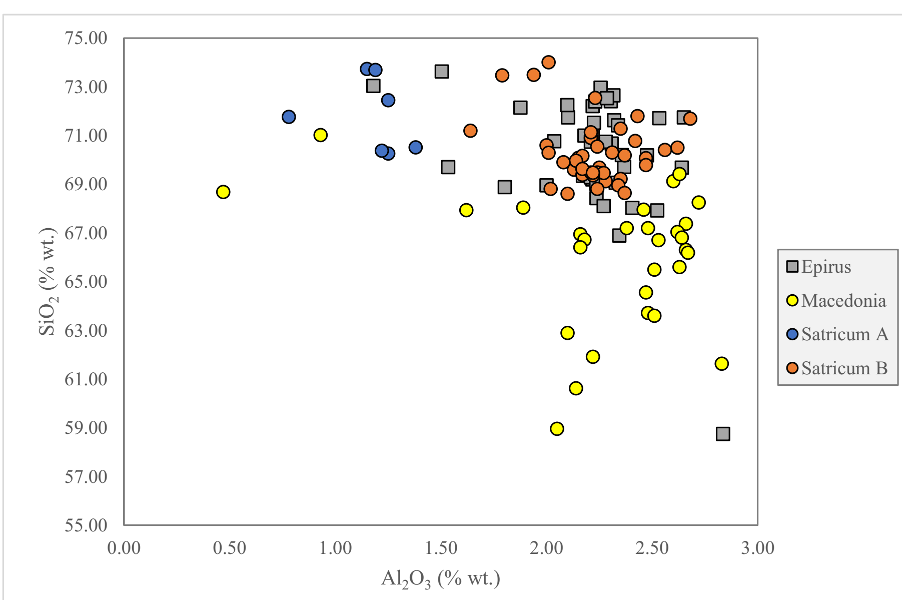

Fig. 6. Correlation between Al_2O_3 and SiO_2 for the Epirotic samples and compared with samples from Macedonia (Blomme et al., 2017) and Satricum (Oikonomou et al., 2016).

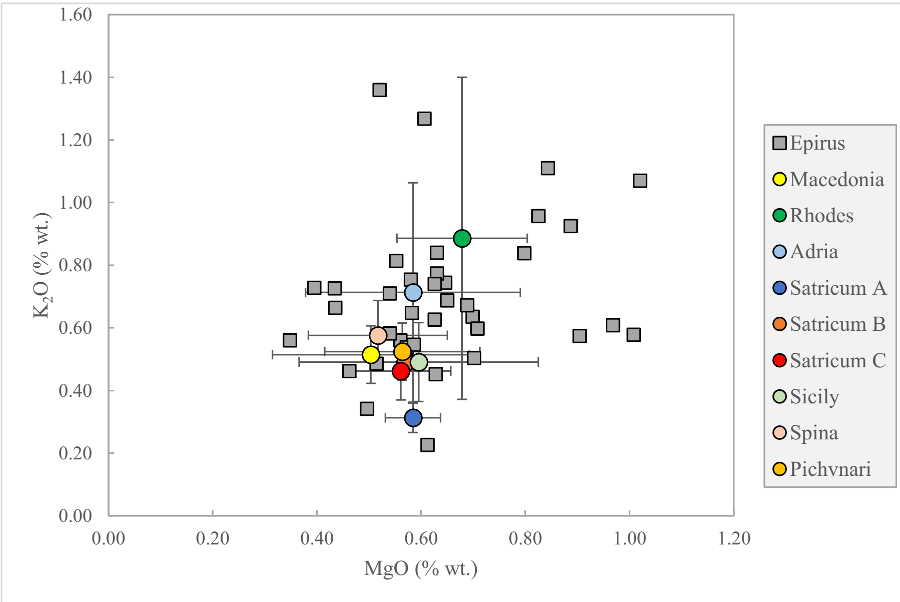

Fig. 7. All samples fall in the natron area having K_2O and MgO contents less than 1.4% and 1.2% wt. respectively. There is an interesting distinction between samples marked with the dashed ellipsis and lines. The samples between the lines show a negative correlation indicating possible different raw materials or/and different manufacturing procedure.

cobaltiferous alums (Kaczmarczyk, 1986; Henderson, 2013). There is not any obvious correlation between Co and the elements that can be found either in minerals or alums e.g. Al, Mn, Ni, Zn, As and Fe. Furthermore, there are few samples which exhibit strangely high levels of manganese (Mn) (10 samples with values above 6500 ppm two of which have Mn ~1.3 and 1.5% wt.). Again, Co is not correlated with Mn and therefore we cannot say with certainty that the Mn comes from the source of Co. Unusual levels of Mn have been noted also by Shortland and Eremin (2006) in late Bronze Age Glass from Egypt and justified probably as a deliberate addition for some as yet unexplained reason. Some of these also exhibit slightly elevated values of barium (Ba) which can be linked to the use of mineral psilomelane ($(Ba,H_2O)2Mn_5O_{10}$) (Shortland and Eremin, 2006).

4. Conclusions

The present paper is a first attempt to identify the technology and provenance of an assemblage of 40 fragments of core formed vessels, with an extensive scientific approach, which belong to the Mediterranean Group II-III industry and were excavated in Hellenistic sites in Epirus region, north west Greece.

The study of major, minor and trace elements of the aforementioned samples revealed very interesting information and correlations with already published data shedding light on the technology and provenance of core formed vessels.

According to the major and minor elements that are associated with the source of silica, i.e. sand, there is a choice for purer sands during this period while earlier samples exhibit totally different patterns. This enforces the theory that the three consecutive core formed industries were independent, using different raw materials and therefore most likely they took place in totally different areas reinforcing the archaeological interpretations.

The majority of the Epirotic samples, due to their technological similarities with Italian samples (Satricum samples, Group B according to Oikonomou et al., 2016) in terms of both major-minor elements and more importantly trace elements we may assume they have an Italian

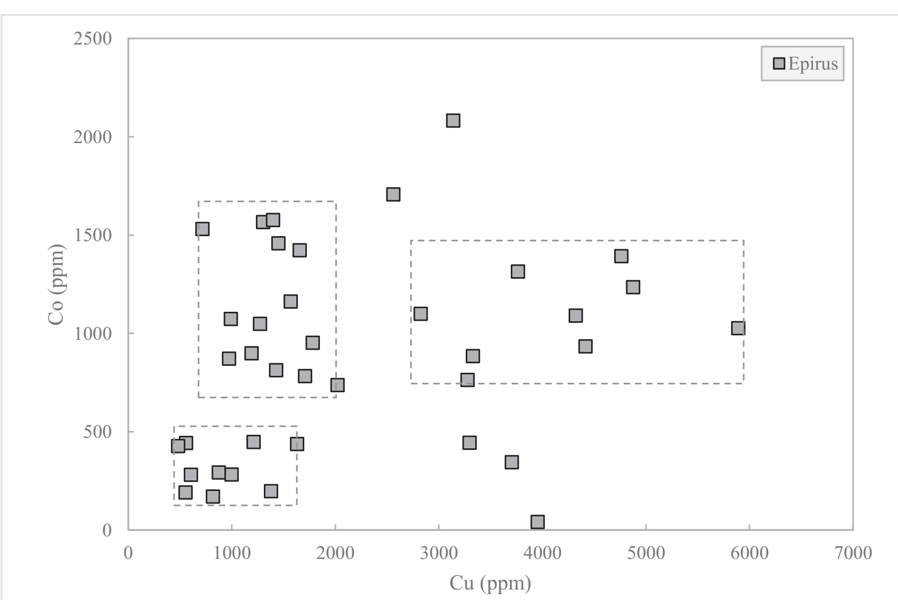

Fig. 8. Correlation between the two responsible elements (Co and Cu) for the blue coloration of the Epirotic samples. Three different groups of samples can be distinguished indicating possible different sources of colorants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

origin. Italy and especially south Italy (Magna Grecia) had long socio-economic, political and trade relations with Greece and especially Epirus during the reign of King Phyrrus. Furthermore, a part of the Epirotic samples (samples from Cassope) have similar chemical fingerprint with samples having an Egyptian origin indicating the same provenance.

Finally, the coloration of the samples is due to the simultaneous presence of both Co and Cu and the samples have the tendency to form three different groups, having different composition of these two elements indicating use of possible different source of colorants. The coloration could have been done either in a primary or a secondary stage.

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