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Ceramic fabrics and lead glazes of late medieval redware pots in the Helsinki, Turku and Tallinn regions (ED-XRF, SEM-EDS)

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A R T I C L E I N F O

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A B S T R A C T

We report on ceramic and glaze chemical and technological data on lead-glazed redware pottery, sampled from late medieval, ca. 14th–17th century CE contexts at five sites across the Gulf of Finland, in modern Finland and Estonia. Redware pots first arrived in this region as Scandinavian and Continental imports, and their local manufacture was established in the 15th–16th centuries. We aimed to chemically characterize ceramic and glaze recipes, distinguish between local and imported redware pots at the sites, and to examine glaze preparation and application practices used. Altogether 34 sherds of ceramic artefacts from three hamlet sites in the Helsinki region (Gubbacka, Mankby and Mårtensby), and the towns of Turku and Tallinn were geochemically and microstructurally analysed by energy-dispersive X-ray fluorescence spectrometry (ED-XRF) and scanning electron microscopy with energy-dispersive spectrometry (SEM-EDS). The majority of the analysed pots were made of clay originating from the Gulf of Finland region, produced at least in Turku and highly likely in Tallinn. Redware was also exchanged between these trading areas. High-lead-content ($PbO < 67$ wt%) glazes, sometimes opacified with tin, were applied as lead-oxide itself or as a lead-oxide-plus-sand mixture on unfired non-calcareous, iron-rich ceramic bodies. This glazing technology to produce impermeable pots was achievable at relatively low temperatures and cost, hence it was commonly adopted by ceramic producers in the North, and stayed in vogue for centuries. Redware pots from different sources appear visually and morphologically related, yet microstructural inspection reveals varied glazing technologies.

1. Introduction and aims

In this article, we examine pottery and glaze recipes used in medieval redware pots recovered from mainly 14th–17th century CE contexts at archaeological sites around Helsinki, Turku and Tallinn, located in modern Finland and Estonia, on the northern and southern coasts of the Gulf of Finland (Fig. 1). Redware pots – often glazed, reddish-coloured, earthenware tripod cooking pots – frequently occur in late medieval contexts, representing early glazing technology in Northern Europe. The lead-glazed earthenware ceramic tradition was initiated in Western Europe (British Isles, France) between the 9th and 11th centuries CE, spreading to the Low Countries and Germany in the course of the 12th century (see Bliek, 1989; McCarthy and Brooks, 1988; Kilmurry, 1980). In southern Scandinavia and on the southeast coast of the Baltic Sea, production of these popular utensils started in the 13th and 14th centuries – it has been suggested that the technology was brought by specialist craftsmen migrating from continental Europe (see Davey and Hodges, 1983; Gaimster, 1997; 1999; Elfwendahl, 1999; Holmqvist et al., 2014). The first redware pots in the Gulf of Finland region were imports from Southern Baltic or Scandinavian production areas, but it is difficult to visually differentiate between separate sources due to the stylistic and morphological similarity between products of different manufacturers (see Christensen et al., 1994; Niukkanen, 2000; 2007; Bergold et al., 2004; Gaimster, 2007). Written sources mention a potter's workshop in Tallinn as early as the 14th century and in Stockholm in 1479 (Johansson, 2007: 52; Russow, 2007: 69; Brorsson, 2016), without

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Fig. 1. Map of the sampled sites (circles) and locations mentioned in the text.

mentioning what kind of pottery was made. From the archaeological sources, clear growth in the use of redware in Tallinn is visible from the second half of the 15th century (Russow et al., 2019: 196), although the direct evidence of medieval local production of redware (kilns, tools, wasters, etc.) is still lacking. In Finland, there is a notable increase in redware sherds encountered in the 15th century contexts in the town of Turku, and this has been interpreted as a possible marker of locally established manufacture of redware pottery (Pihlman, 1989: 104). However, the earliest direct evidence of redware manufacture in Turku dates only to the turn of the 16th and 17th centuries (Tulkki, 2003).

Our aim was to identify different ceramic and glaze recipes, distinguish between local and imported redware pots at the sampled sites, and to examine glaze preparation and application practices used in redware manufacture. Altogether 34 sherds of ceramic artefacts (Table 1, Figs. 2 and 3) were sampled from excavation materials from three hamlet sites (Gubbacka, Mankby and Mårtensby) located in the modern greater Helsinki area on the northern coast of the Gulf of Finland, and the towns of Turku and Tallinn, in modern coastal Finland and Estonia, respectively (Fig. 1). The ceramic samples were prepared as polished cross-sections and subjected to geochemical and microstructural characterization via energy-dispersive X-ray fluorescence spectrometry (ED-XRF) and scanning electron with energy-dispersive spectrometry (SEM-EDS) at University of Helsinki laboratories. The samples were assigned to fabric groups indicated by statistical processing of the geochemical ED-XRF data, confirmed by ceramic paste and mineralogical compositions acquired by SEM-EDS. The glaze composition, preparation and application methods were analysed using SEM-EDS imaging and microchemical tools.

2. Archaeological sites and ceramic artefacts

The medieval hamlet site of Gubbacka is located on a hill in the modern port of Helsinki (the Vuosaari district), with direct access to the sea (see the site locations in Fig. 1). Gubbacka was established by Swedish settlers in the late 13th century and deserted by the late 16th century. The Gubbacka excavations in 2002–2003 and 2008–2010 produced a large assemblage of redware pottery finds, dating mainly from the late 14th to the 16th centuries CE (Koivisto et al., 2010; Holmqvist et al., 2014; see Fig. 2 for sample nos. 1–10).

In general, most of the pots sampled for this project represent different ceramic morphologies and typo-chronologies, and are often fairly small-sized rim or body sherds. Thus, it is not always possible to determine the vessel morphology with certainty. Most of the ceramic sherds from Gubbacka have reddish or reddish-greyish fabrics and glazed interiors (see Table 1 for sample descriptions). Two samples (nos. 3 and 7) are unglazed greyish coarseware sherds, the former dated to the 14th century and the latter, of "Iron Age" type fabric, presumably local and TL dated to the 15th century (see Holmqvist et al., 2014). Certain glazed sherds (nos. 4 and 8–10) were selected as suspected imports based on their visual appearance and fabric quality. In addition to the artefacts, fragments of burnt clay daubs (nos. 35–36) were sampled from two furnaces at the Gubbacka site (dating to the 15th and 14th–17th centuries, respectively) as likely representatives of the local clay composition.

Mankby is located on a wooded hill in western Espoo (west of Helsinki), along the River Mankki close to the Espoo bay. Mankby was founded by Swedish settlers by the early 13th century, and the village site was abandoned in the 1550s. The site was excavated in 2007–2013, and the rich find material included redwares dating to the 15th and 16th centuries. The large number of imported objects found suggests that the people living in Mankby were actively involved in trade (Harjula et al., 2016). Five pots (Fig. 2, Table 1, nos. 11–15) were selected from the assemblage at Mankby. Glazed sherd no. 15 has an unusual, overlapping rim profile and a yellowish glaze. It is uncertain whether the handle fragments (nos. 13–14) belonged to glazed or unglazed pots.

The urban settlement of Tallinn on the shore of Tallinn Bay was established some time after the Christianization of Northern Estonia in 1219/1220 and acted as a busy international merchant town from the mid-13th century at latest (Russow, 2016). From the origins of the town until the early modern period, its population was very diverse and attracted migration from Scandinavia, coastal Finland, and northern Germany (Johansen, 1951). The redware sherds (nos. 16–20, no. 18 being a glazed floor tile; Table 1) sampled from Tallinn date to the late 14th century – first half of 15th century CE, and were found at a suburban site that was situated not far from the river crossing in the medieval period. The location and the character of the main structure, and

Table 2
ED-XRF results of ceramic fabrics (mean values of 3–5 measurements per sample). Results normalized to 100%, sample order and group allocations as indicated by the CA dendrogram.

No	Date	Glaze	Site	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	P_2O_5 (%)	SO_3 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)	SiO_2 /Al_2O_3	NiO (ppm)	CuO (ppm)	ZnO (ppm)	Rb_2O (ppm)	SrO (ppm)	Y_2O_3 (ppm)	ZrO_2 (ppm)	BaO (ppm)
Fabric 1a																							
33	1550–1650	x	Mårtensby	1.48	1.70	15.50	71.10	0.90	0.18	2.69	0.94	0.62	0.03	5.40	4.59	14	2	86	109	87	45	363	264
34	1550–1650	x	Mårtensby	1.61	1.79	15.60	70.50	0.82	0.20	2.67	0.97	0.61	0.03	5.52	4.52		1	116	111	83	33	363	295
12	c. 1450–1550	–	Mankby	1.38	1.96	16.90	68.90	0.75	0.20	3.22	0.57	0.61	0.03	6.28	4.08	20	74	86	129	78	27	273	358
7	15th c.	–	Gubbacka	1.97	1.84	18.00	66.50	0.57	0.29	3.00	1.08	0.69	0.03	6.43	3.69		42	106	136	106	35	273	528
35	15th–16th c.	–	Gubbacka daub	4.45	1.78	13.60	67.00	0.70	0.28	3.62	2.18	0.61	0.04	5.29	4.93			110	154	268	23	395	599
36	15th–16th c.	–	Gubbacka daub	3.41	1.91	14.80	65.50	1.65	0.29	3.26	2.05	0.62	0.05	5.95	4.43		3	163	129	264	24	287	634
15	16th c.?	x	Mankby	3.31	2.22	15.60	65.30	1.01	0.19	3.65	1.48	0.58	0.06	6.38	4.19			112	156	133	38	255	471
27	1750–1800	x	Turku	3.77	2.23	15.40	66.60	0.50	0.26	3.23	0.97	0.55	0.03	6.00	4.32		78	89	152	133	35	298	562
13	c. 1450–1550	–	Mankby	2.73	2.58	15.00	67.80	0.72	0.19	3.19	1.18	0.59	0.05	5.77	4.52	15	25	84	116	134	35	259	421
11	c. 1450–1550	x	Mankby	3.46	2.18	15.60	67.20	0.76	0.16	2.79	1.29	0.50	0.06	5.72	4.31	51	10	92	149	116	33	252	473
28	1750–1800	–	Turku	3.68	2.65	15.30	66.00	0.35	0.24	3.02	1.11	0.52	0.06	6.76	4.31	1	22	89	150	120	30	204	458
3	14th c.	–	Gubbacka	2.70	1.81	18.10	61.70	3.59	0.27	2.82	1.03	0.60	0.02	7.07	3.41		43	93	138	160	30	250	593
22	late 13th c.	–	Tallinn	3.12	2.41	17.40	61.70	1.55	0.21	3.43	1.94	0.52	0.07	7.43	3.55	29	40	100	137	168	34	266	485
			μ (n = 13)	**2.85**	**2.08**	**15.91**	**66.60**	**1.07**	**0.23**	**3.12**	**1.29**	**0.59**	**0.04**	**6.15**	**4.22**	**22**	**31**	**102**	**136**	**142**	**32**	**288**	**472**
			σ	1.0	0.3	1.3	2.8	0.8	0.0	0.3	0.5	0.1	0.0	0.7	0.4	17.0	27.4	21.3	16.3	61.3	5.9	54.4	115.0
Fabric 1b																							
29	Late 16th–early 17th c.	–	Turku	3.53	3.37	17.40	61.90	0.41	0.18	3.29	1.33	0.68	0.06	7.48	3.56		33	136	162	124	34	241	481
30	Late 16th–early 17th c.	–	Turku	3.68	3.33	17.00	62.50	0.41	0.17	3.31	1.34	0.64	0.05	7.32	3.68	44	27	114	155	125	34	229	493
31	17th c.?	x	Mårtensby	3.69	3.88	18.90	59.10	0.70	0.09	3.43	1.32	0.69	0.05	7.74	3.13		115	92	149	145	31	182	550
32	Iron Age?	–	Mårtensby	3.60	4.01	18.80	55.40	2.36	0.26	3.16	1.75	0.82	0.06	9.54	2.95	34	68	178	170	140	19	185	444
			μ (n = 4)	**3.63**	**3.65**	**18.03**	**59.73**	**0.97**	**0.17**	**3.30**	**1.44**	**0.71**	**0.06**	**8.02**	**3.33**	**39**	**61**	**130**	**159**	**134**	**30**	**209**	**492**
			σ	0.1	0.3	1.0	3.2	0.9	0.1	0.1	0.2	0.1	0.0	1.0	0.3	7.1	40.4	36.7	9.1	10.6	7.1	30.2	43.9
Fabric 2a																							
8	Early 16th c.	x	Gubbacka	1.61	1.07	10.50	77.70	1.16	0.22	2.12	0.56	0.69	0.03	5.07	7.40		13	76	88	102	26	401	324
10	Early 16th c.	x	Gubbacka		0.98	10.90	77.90	0.79	0.21	2.67	0.75	0.57	0.03	4.80	7.15		36	72	97	103	41	428	417
19	Late 14th–early 15th c.	x	Tallinn	1.60	1.54	12.30	74.60	0.48	0.19	2.57	1.22	0.59	0.05	5.03	6.07		19	53	95	79	34	356	350
26	1550–1650	x	Turku	1.63	1.50	13.10	75.00	0.44	0.23	2.35	0.87	0.59	0.04	4.60	5.73		31	95	116	93	59	389	279
16	Late 14th–early 15th c.	x	Tallinn	1.66	1.52	12.90	73.60	0.73	0.26	2.59	1.64	0.58	0.02	4.57	5.71	22	75	97	104	85	26	287	351
24	Late 15th c.	x	Turku	2.22	1.43	11.60	74.20	0.77	0.40	2.57	1.33	0.59	0.06	4.96	6.40	5	40	88	94	120	51	419	399
23	Late 15th c.	x	Turku	2.01	1.34	12.70	74.80	0.32	0.33	2.78	0.78	0.53	0.03	4.60	5.89	20	155	59	99	85	40	336	385
18	Late 14th–early 15th c.	x	Tallinn	1.82	1.73	12.40	72.20	1.18	0.44	1.81	3.62	0.54	0.06	3.81	5.82	17	35	123	103	149	41	292	404
6	c. 1450–1600	x	Gubbacka	1.92	1.52	13.70	70.90	0.65	0.04	2.53	1.04	0.53	0.02	5.70	5.18	16	49	65	112	84	3	330	239
			μ (n = 9)	**1.81**	**1.40**	**12.23**	**74.54**	**0.72**	**0.26**	**2.44**	**1.31**	**0.58**	**0.04**	**4.79**	**6.15**	**16**	**50**	**81**	**101**	**100**	**36**	**360**	**350**
			σ	0.2	0.2	1.0	2.3	0.3	0.1	0.3	0.9	0.0	0.0	0.5	0.7	6.6	43.1	22.1	8.9	22.4	16.2	52.5	60.3
Fabric 2b																							
1	16th c.	x	Gubbacka		1.56	14.70	71.90	0.62	0.20	3.13	0.76	0.75	0.02	5.95	4.89		21	77	130	101	42	424	433
4	16th c.	x	Gubbacka	1.66	1.47	14.50	71.10	1.30	0.22	2.75	0.71	0.78	0.02	6.04	4.90	15	16	99	110	89	41	425	611
2	c. 1450–1600	x	Gubbacka	1.78	1.37	14.20	71.10	0.60	0.30	3.49	1.06	0.69	0.03	6.19	5.01		42	90	124	110	46	385	419
14	c. 1450–1550	?	Mankby	2.89	2.10	14.00	68.70	0.84	0.17	3.09	1.27	0.66	0.05	5.93	4.91		28	111	126	144	30	351	399
17	Late 14th–early 15th c.	x	Tallinn	1.86	1.96	14.30	70.50	0.65	0.29	2.69	1.87	0.68	0.05	6.21	4.93	89	11	92	109	126	40	322	341
9	15th c.	x	Gubbacka	1.72	1.57	13.50	69.70	2.65	0.23	2.74	1.35	0.63	0.02	6.05	5.16	9		109	101	160	42	362	601
20	Late 14th–early 15th c.	x	Tallinn	1.76	1.64	12.50	73.00	0.56	0.24	2.84	1.30	0.60	0.04	5.65	5.84	2	157	74	117	106	42	282	367
25	16th c.	x	Turku	1.81	1.55	12.20	70.90	1.68	0.44	2.24	4.20	0.63	0.04	4.46	5.81	4	14	58	99	124	50	312	265
5	c. 1450–1600	x	Gubbacka	1.92	1.46	12.60	74.10	0.51	0.18	2.67	1.09	0.70	0.13	5.35	5.88	15	32	97	112	88	48	288	398
			μ (n = 9)	**1.93**	**1.63**	**13.61**	**71.22**	**1.05**	**0.25**	**2.85**	**1.51**	**0.68**	**0.04**	**5.76**	**5.26**	**22**	**40**	**90**	**114**	**116**	**42**	**350**	**426**
			σ	0.4	0.2	0.9	1.6	0.7	0.1	0.4	1.1	0.1	0.0	0.6	0.4	33.1	48.3	17.3	10.9	24.4	5.7	53.8	113.5
Fabric 3																							
21	Late 14th–early 15th c.	x	Tallinn	2.93	2.49	16.40	49.82	0.48	1.35	2.94	0.90	0.43	0.03	13.46	3.04	36	24	134	823	729	352	1568	3451

Table 1
List of the analysed ceramic artefacts with context information.

No	Context / Catalogue ID	Site	Description	Glazed	Suggested Date
1	KM2008043:49	Gubbacka	Pot rim, reddish, fine-grained ware, wheel-made	Interior	16th c.
2	KM2008043:86	Gubbacka	Pot (?) bodysherd, very soft, coarse material, light reddish ware	Interior	c. 1450–1600 (context)
3	KM2008043:94	Gubbacka	Pot rim, reddish-brown coarse ware	Unglazed	14th c.
4	KM2009083:122	Gubbacka	Pot? Bodysherd, yellow–brown coarse ware	Interior	16th c.
5	KM2009083:138	Gubbacka	Pot bodysherd, reddish-bown ware, hard fired	Interior	c. 1450–1600 (context)
6	KM2010077:26	Gubbacka	Pot bodysherd, reddish ware	Both surfaces	c. 1450–1600 (context)
7	KM2010077:181	Gubbacka	Bodysherd, coarse grey earthenware	Unglazed	15th c. (TL dated)
8	KM2010077:233	Gubbacka	Pot bodysherd, light reddish relatively fine grained ware	Interior	Early 16th c.
9	KM2010077:240	Gubbacka	Pot bodysherd, yellowish/reddish fine grained ware	Both surfaces	15th c.
10	KM2010077:255	Gubbacka	Pot bodysherd, wheel-made, ligh reddish, relatively fine-grained ware	Interior, glaze spots on exterior	Early 16th c.
11	KM2008044:277	Mankby	Pot bodysherd, reddish/brownish ware, hard fired	Interior	c. 1450–1550 (context)
12	KM2008044:376	Mankby	Pot bodysherd, reddish fine-grained ware	Unglazed	c. 1450–1550 (context)
13	KM2008044:401	Mankby	Pot handle, reddish ware	Unglazed handle	c. 1450–1550 (context)
14	KM2009032:35	Mankby	Pot handle, light reddish ware	Unglazed handle	c. 1450–1550 (context)
15	KM2011014:187	Mankby	Pot rim, overlapping rim, light reddish/brownish ware	Interior, glaze spots on exterior	16th c.?
16	AI7032:1557	Tallinn	Pot, reddish/brownish ware	Interior and rim	End of the 14th–first half of the 15th c.
17	AI7032:1623	Tallinn	Pot, dark greyish fine-grained ware, wheel-made, hard fired	Interior and rim	End of the 14th–first half of the 15th c.
18	AI7032:1623	Tallinn	Floor tile, dark reddish coarse ware	Exterior	End of the 14th–first half of the 15th c.
19	AI7032:1625	Tallinn	Pot, reddish fine-grained ware	Interior and rim	End of the 14th–first half of the 15th c.
20	AI7032:1175	Tallinn	Pot (?) bodysherd, light reddish ware, wheel-made	Interior	End of the 14th–first half of the 15th c.
21	AI6648:8	Tallinn Sulevimägi 4/6	Ceramic cupel, coarse brown/red ware	Coating (glaze?) on both surfaces	
22	AI6713: 270	Tallinn Apteegi street	Tripod pot rim, coarse grained, light reddish ware, grey core, wheel-made	Unglazed	Late 13th c.
23	TMM 22,367 KE1034:006	Turku Tuomiokirkontori	Pot rim, orange fine-grained ware, hard-fired	Interior	Later half of the 15th c.
24	TMM22367 KE2154:001	Turku Tuomiokirkontori	Tripod pot base, fine grained, hard-fired	Interior, glaze spots on exterior	Later half of the 15th c.
25	TMM22196 KE548:003	Turku Rettinginrinne	Tripod pot base, brownish/reddish fine-grained ware, hard-fired	Interior, glaze spots on exterior	16th c.
26	TMM22196 KE551:004	Turku Rettinginrinne	Pot rim, fine light-reddish ware, thin-walled, hard-fired	Interior	1550–1650
27	TMM22890 KE153:010	Turku Linnankatu 35b	Pot bodysherd, light reddish, medium-fine ware, finger impressions, two rings on handles, hard-fired, kiln waste	Glaze spots on both surfaces	1750–1800
28	TMM22890 KE153:052	Turku Linnankatu 35b	Bodysherd, decorative grooves on exterior, wheel-made, fine-grained light reddish ware, hard-fired, kiln waste	Unglazed	1750–1800
29	TMM18335:259	Turku Tuomiokirkkokatu 2–4	Pot rim with broken handle, finger-impressions, wheel-made, fine reddish ware, thin-walled, hard-fired, kiln waste	Unglazed	Late 16th–early 17th c.
30	TMM18335:369	Turku Tuomiokirkkokatu 2–4	Pot rim with handle, finger impressions, wheel-made, light reddish, relatively fine-grained ware, hard-fired, kiln waste	Unglazed	Late 16th–early 17th c.
31	KM2011018:1026	Mårtensby-11 Alue 4	Pot bodysherd and handle	Interior	17th c.?
32	KM39163:686	Mårtensby-12 Alue 4	Grey earthenware bodysherd	Unglazed	Iron Age? Secondary context
33	KM39466:305	Mårtensby-13 Alue 3	Pot bodysherd	Both surfaces?	1550–1650
34	KM39466:317	Märtensby-13 Alue 3	Pot rim	Glazed	1550–1650
35	KM2010077:612 R401	Gubbacka	Clay daub fragment from furnace	Unglazed	15th c.
36	KM2010077:679 R601	Gubbacka	Clay daub fragment from furnace	Unglazed	14th–17th c.

the variety of the artefacts, suggest that a significant proportion of the late medieval finds, including the samples, are connected to an inn or some other public institution (Kadakas et al., 2013; Russow et al., 2013).

The ceramic fragment from Sulevimägi 4/6 (no. 21) comes from a plot beside the town wall that was used by the northwest Russian traders and craftsmen during the 13th and 14th centuries (Lightfoot et al., 2016: 85). This sherd was initially interpreted as production waste of glazed redware but subsequent research revealed that it is a cupel used for making small seed beads. Similar cupels as well as semi-finished products have been found in the Russian quarters in Riga, Latvia and Tartu, Estonia, making it plausible that the Tallinn finds are part of the craft activities of Novgorodian and Pskovian artisans (see Caune, 2004; Russow, 2019). The final Tallinn sample (no. 22) was taken from an unglazed, reddish coarse-ware tripod pot, found almost intact at the corner of a medieval basement at number 5 Apteegi Street, close to the market square and town hall. From the technological and typological standpoint, this pot represents rather typical 13th–14th century kitchenware, used in bulk everywhere around the town, although more sizable and globular in shape than usual. Stylistically, these pots (for basic typology, see Mäll and Russow, 2004: Fig. 5C–E) resemble tripods used in the Roskilde-Lund region in southern Scandinavia (see published in Bencard and Roesdahl, 1972: Cat. no. 29–30; Wahlöö, 1976: Cat. no. 182–184; Johansson, 2013), which might indicate that potters migrated from there when northern Estonia including Tallinn was under the Danish rule (that is, until the mid-14th century). The Tallinn pots are of reddish fabric, and glazed ones (nos. 16, 19, 20) show dark reddish surfaces, excluding pot no. 17 which is dark greyish in colour (with a typical redware rim form), and the floor tile (no. 18) which has a

Fig. 2. Ceramic samples from Gubbacka (nos. 1–10), Mankby (nos. 11–15), and Tallinn (nos. 16–22).

Fig. 3. Ceramic samples from Turku (nos. 23–30), and Mårtensby (nos. 31–34).

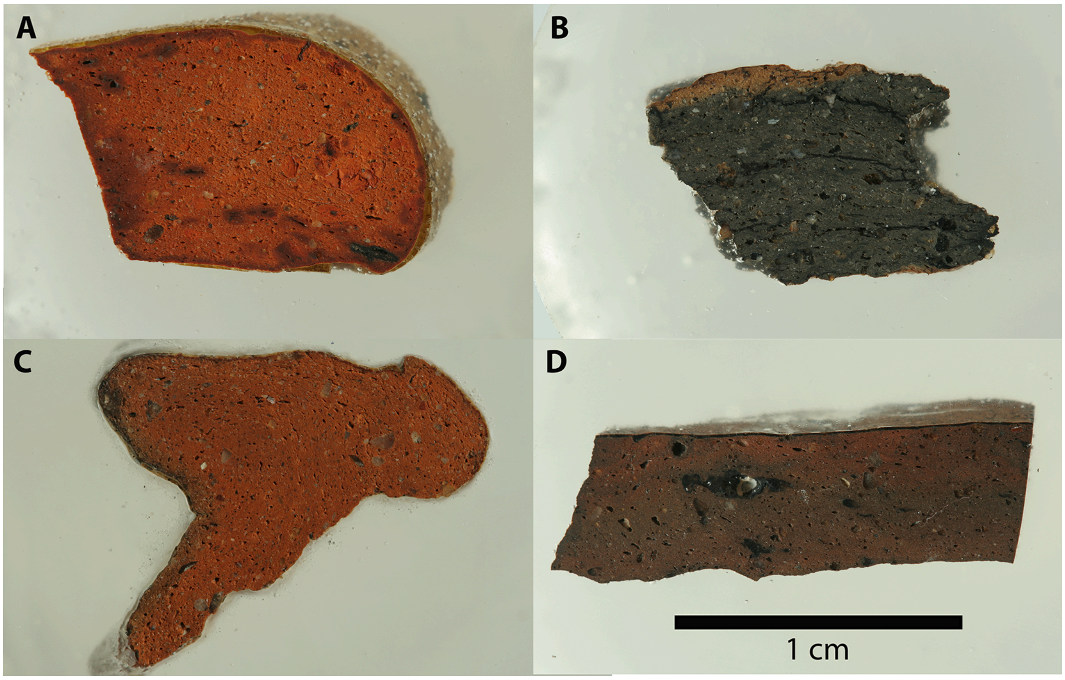

Fig. 4. Ceramic cross-sections of samples in polished resin blocks: A = lead-glazed no. 1 from Gubbacka; B = unglazed no. 7 from Gubbacka, C = tin–lead-glazed no. 15 from Mankby; D = lead-glazed no. 17 from Tallinn.

yellowish glaze.

Eight ceramic samples (nos. 23–30), including rim and handle fragments, were selected from four excavation sites by the Museum Centre of Turku, from contexts dating from the late 15th century until 1800 CE. The medieval town of Turku is located on the southwest coast of Finland on the River Aura (Fig. 1). At the river mouth near the town, there was a Crown castle and the inland roads met in the town. The settlement in the Aura river valley was dense by the end of the Iron Age (ca. 1150/1200 CE). In the 13th century it became the first ecclesiastical centre of Finland: the bishop's residence was built 1.5 km upstream on the cape of Koroinen and around 1300 CE, Turku was founded (Ratilainen et al., 2016; Harjula et al., 2018). In the Middle Ages and long afterwards, Turku was the most prominent town in the eastern province of the Kingdom of Sweden.

Three of the Turku sites are located in the area of the medieval town (Tuomiokirkontori, Rettiginrinne and Tuomiokirkkokatu 2–4), and one in the area inhabited only in post-medieval times (Linnankatu 35b). The Tuomiokirkontori (Cathedral Square) excavations in 2005–2006 were located in the centre of the medieval town, near the cathedral on its southeast, south and southwest sides. The oldest urban deposits discovered date to the early 14th century (Pihlman, 2010). Sherd nos. 23 and 24 are from Tuomiokirkontori deposits dating to the second half of the 15th century, found from the south/southeast side of the cathedral. The Rettiginrinne (Rettig Rise) excavations in 2000–2001 were carried out on the edge of the medieval Convent quarter, under Vartiovuori (Guard Hill), in the area built in the second half of the 14th century (Pihlman, 2010: 19–21; Ratilainen, 2010: 43-44; Saloranta, 2010: 65). Sherd no. 25 from this site was discovered in a 16th-century deposit, while no. 26 is from a deposit dated between ca. 1550–1650.

The excavations at the plot at number 35b Linnankatu (Castle Street) were executed in 2012, on the western side of the River Aura, ca. 1.5 km from the cathedral towards the river mouth, on the edge of the town built in the second half of the 17th century. Written sources revealed that pot makers had lived there for five generations from the 1680s until 1832. The analysed fragments (nos. 27 and 28) were from unfinished vessels (kiln waste). Their context dates to the second half of the 18th century and was rich in fragments of stove tiles and pottery broken during the production process (Pihlman and Savolainen, 2019).

The excavations on the northern edge of the medieval town on the Tuomiokirkko (Cathedral) Street were conducted in 1976–1977. Sherd nos. 29 and 30 are unfinished objects derived from a deposit containing a large amount of stove tile and pottery production waste, the waste dating from the turn of the 16th and 17th centuries (Tulkki, 2003). Of the Turku pots, nos. 23–27 have greyish, glazed surfaces, whereas nos. 28–30 are unglazed with a light reddish fabric.

Furthermore, four sherds (nos. 31–34; Fig. 3) dated to the turn of the 16th and 17th centuries were sampled from the village of Mårtensby, two of which (nos. 31 and 33) had dark greyish glazed surfaces. Mårtensby is in the countryside around the modern-day town of Vantaa, on the shore of River Vantaa some 10 km from the seashore. The village was founded by Swedish immigrants in the 13th century. Excavations at one of the farm sites, Lillas, were carried out in 2011–2013, and a large assemblage of redware pottery was collected, dating mainly between the 16th and 18th centuries (Kadakas and Väisänen, 2012; Koivisto, 2014; Heinonen, 2015; Väisänen, 2016). The inhabitants of Lillas were engaged in large-scale peasant trade in the early 16th century and had lively contacts to Tallinn. In those days, Tallinn was the town nearest to the villages in what is now the Helsinki region, situated only 90 km south across the Gulf of Finland (one day's journey) in modern Estonia. Active contacts across the Gulf of Finland are recorded in written sources between the 14th and 16th centuries, and it has been suggested that redwares were first brought to Finland from or via Tallinn (Salminen, 2012; Holmqvist et al., 2014).

3. Methods

3.1. Sample preparation

Redware sherds in archaeological contexts especially in Finland are often small-sized and thus do not allow extensive invasive sampling to produce a homogeneous sample for quantitative analysis (e.g. minimum of 5 g of material for pressed pellet preparation, see Holmqvist, 2017 and references therein). Furthermore, cross-section samples of ceramics facilitate the analysis of different phases, e.g. the glaze coatings, glaze-fabric-interfaces and mineralogy, and it is also possible to focus the paste/fabric analysis on the fabric cores, which are less sensitive to post-

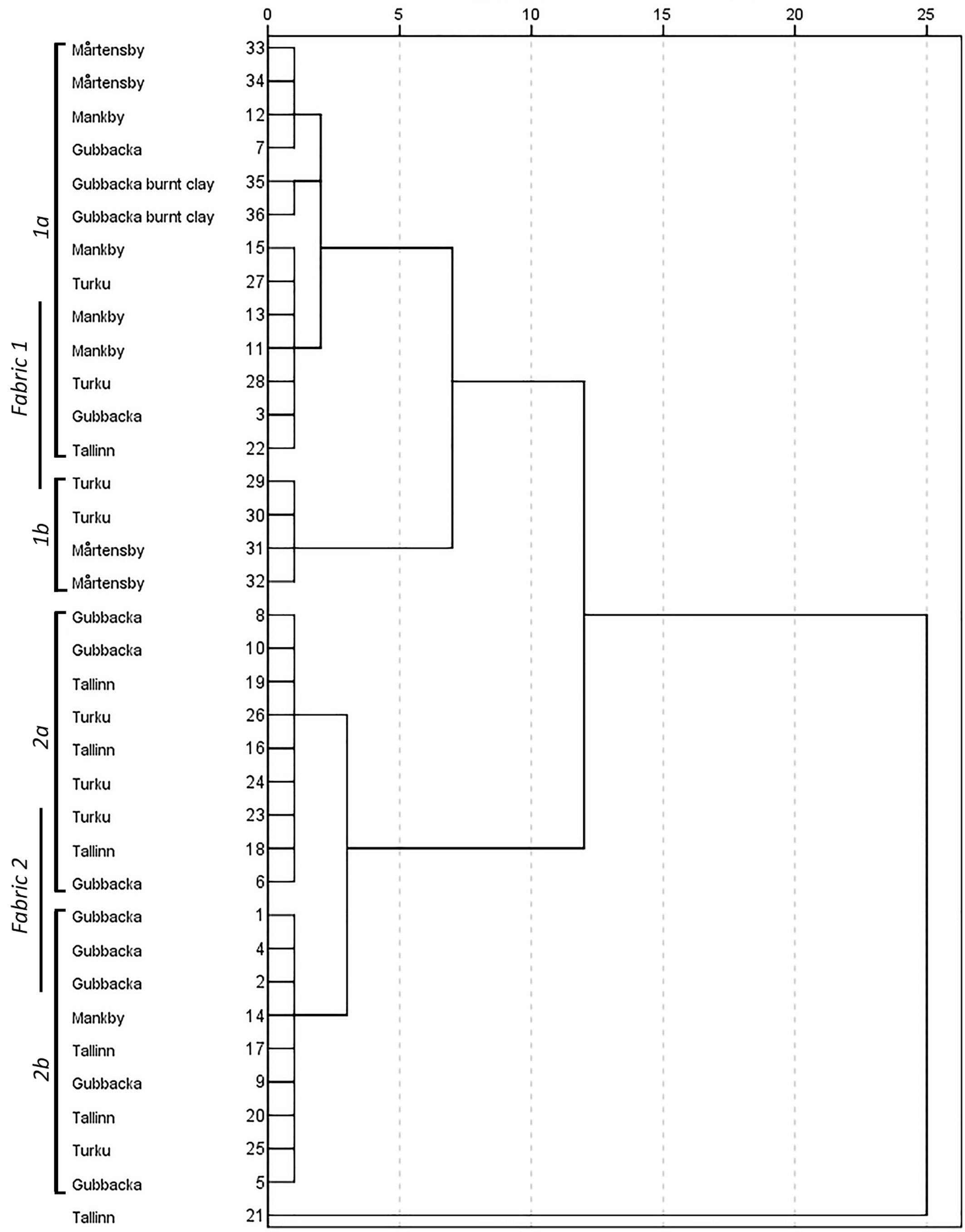

Fig. 5. Cluster analysis dendrogram of the ED-XRF ceramic fabric data showing two main clusters with subgroups 1a–b and 2–b.

depositional or coating-absorbed elemental contamination than near-surface areas. Therefore, we chose a sampling strategy which maximized sample preservation (a profile cut of ca. 1 cm) and the number of applicable analytical methods (visual and microscopic examination of fabrics, ED-XRF spot analysis, SEM-EDS microstructural and microchemical analysis) as well as allowing us to control the lead enrichment in the ceramic data (by avoiding areas near the coated surfaces in paste/fabric analysis). In addition, chlorine values, possibly enriched by the resin material especially in the case of porous ceramics, and P_2O_5 values prone to post-depositional variation, were excluded from the statistical tests.

The analytical specimens were cut with a Buehler diamond saw perpendicular to the vessel surface and mounted in resin blocks (Fig. 4), allowing sample longevity and repeated analysis. The cross-sections were then polished with diamond paste (down to a grain size of 0.5 μm) and carbon coated for the SEM-EDS analysis to eliminate charging effects.

3.2. ED-XRF analysis of ceramic cross-sections

The instrument utilized for the ED-XRF analysis was a Rigaku NEX-DE VS bench top ED-XRF spectrometer based in the Laboratory of Archaeology at the University of Helsinki. The instrument was operated in point analysis mode with the beam diameter adjusted to 1 mm to analyse major, minor and trace elemental concentrations of the ceramic fabrics. The reported results are normalized mean values of 3–5 measured points, selected carefully avoiding large inclusions and areas close to the vessel surfaces to avoid mineralogical effects and surface

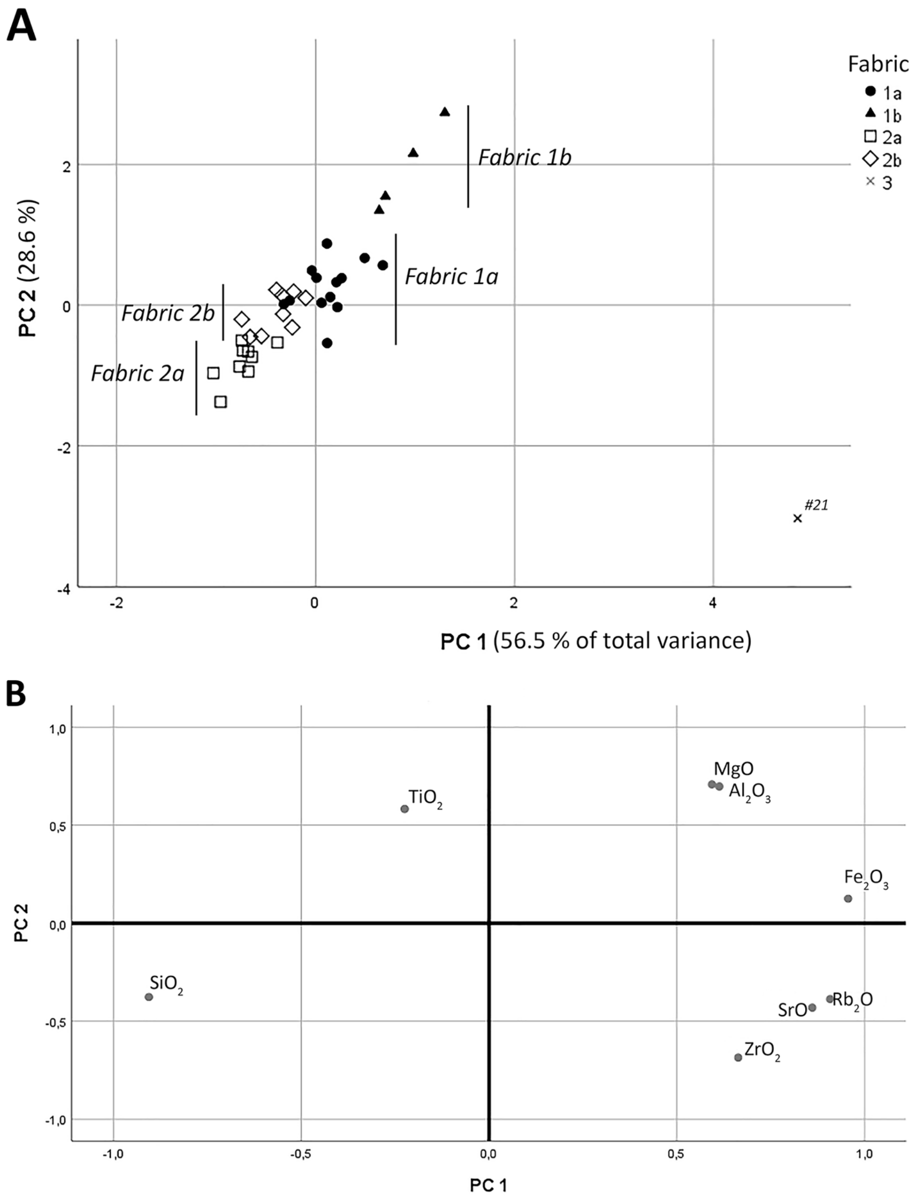

Fig. 6. Principal component analysis plots of ED-XRF ceramic fabric data, a) samples marked by CA groupings (the first three components represent 94.43% of the total variation); b) the component plot.

contamination, particularly absorption of Pb from the glaze coatings. The data was acquired in a helium atmosphere and using a tube voltage of 60 kV, 35 kV, 6.5 kV and a measuring time of 60, 60 and 100 s for high-Z, mid-Z and low-Z elements, respectively. The results were quantified using the spectrometer's software and fundamental parameters (see Supplementary Table 1 for the complete ED-XRF data set).

The data quality was controlled by analysing a standard reference sample, NIST 76a (see Supplementary Table 2). The fabric data of the glazed artefacts shows increased Pb values deriving from the coatings (the most extreme effect is seen on nos. 6 and 21), yet unaffecting the data patterns when normalized with or without Pb. The precision and accuracy tests (Supplementary Table 2) on the standard reference material, Burnt Refractory NIST 76a, show good precision values with relative variation coefficients being below 1.5% for all the oxides with concentration values above 0.3 wt%. For the accuracy tests, the average results compared to the certified value show relative errors lower than 10% for all reported oxides with contents above 0.5 wt%.

The IBM SPSS 25 software was used for statistical data processing. The fabric groups of the samples were formed based on the cluster analysis (CA) groupings of the ED-XRF data using Ward's Squared Euclidian method (see cluster analysis dendrogram in Fig. 5), and the data patterns were further tested using principal component analysis (PCA, Fig. 6a–b). The ED-XRF measured concentrations of MgO, Al_2O_3, SiO_2, TiO_2, Fe_2O_3, ZrO_2, Rb_2O and SrO (Table 2) were used in both statistical approaches. The groups indicated by the ED-XRF data were further verified with the mineralogical and ceramic paste compositional data acquired by SEM-EDS.

3.3. SEM-EDS analysis of ceramic bodies, mineralogy and glaze coatings

The instrument applied in the SEM-EDS data acquisition was a Hitachi S-4800 high-resolution field emission scanning electron microscope (FE-SEM) based in the Laboratory of Inorganic Chemistry at the University of Helsinki. The samples were examined using both backscatter (BSE) and secondary electron (SE) imaging of the ceramic cross-sections in order to observe the ceramic microstructure, grain size, surface treatment, and mineral composition. These features were documented by micrographs taken with different magnifications. Prior

Table 3
SEM-EDS data of the ceramic pastes. All oxides normalized to 100%. Reported values are means of 3–5 measurements expressed as wt% of oxides (by stoichiometry). Sample order and group allocations as indicated by the CA dendrogram.

No	Site	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	SiO_2 / Al_2O_3	P_2O_5 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	FeO (%)
Fabric 1a											
33	Mårtensby	0.76	1.93	17.63	62.76	3.56	0.81	3.99	1.11	1.00	10.01
34	Mårtensby	0.85	1.98	17.56	65.05	3.70	0.79	4.06	1.10	0.92	7.69
12	Mankby	1.20	2.04	18.80	63.31	3.37	0.50	4.30	1.02	1.02	7.82
7	Gubbacka	1.04	1.79	18.94	62.90	3.32	1.53	4.03	1.03	1.18	7.56
35	Gubbacka daubt	2.47	1.95	13.88	69.62	5.02	0.64	3.06	1.88	0.88	5.63
36	Gubbacka daubt	1.76	2.32	15.82	65.59	4.15	1.17	3.96	1.68	0.90	6.79
15	Mankby	1.49	2.40	15.79	63.34	4.01	0.80	5.08	1.30	0.92	8.88
27	Turku	1.65	2.79	17.47	63.14	3.61	0.39	4.51	1.12	0.87	8.07
13	Mankby	1.38	3.31	17.55	64.30	3.66	0.70	3.99	1.27	0.82	6.67
11	Mankby	1.60	2.34	17.05	62.87	3.69	0.95	4.82	1.96	0.88	7.55
28	Turku	1.71	2.99	17.28	62.98	3.64	0.37	4.40	1.07	0.85	8.36
3	Gubbacka	0.93	2.04	17.70	59.84	3.38	3.22	4.24	1.18	1.09	9.76
22	Tallinn	0.93	2.63	19.15	60.86	3.18	0.85	4.52	1.87	0.99	8.20
	μ (n = 13)	**1.37**	**2.35**	**17.28**	**63.58**	**3.72**	**0.98**	**4.23**	**1.35**	**0.95**	**7.92**
	σ	0.48	0.46	1.44	2.36	0.47	0.74	0.49	0.36	0.10	1.20
Fabric 1b											
29	Turku	1.66	3.36	18.50	59.98	3.24	0.22	4.91	1.49	1.06	8.83
30	Turku	1.67	3.57	18.71	59.54	3.18	0.33	4.94	1.30	0.95	8.99
31	Mårtensby	1.58	3.41	19.18	58.74	3.06	0.66	4.93	1.39	1.04	9.06
32	Mårtensby	1.58	3.96	19.47	56.29	2.89	1.54	4.58	1.69	1.14	9.74
	μ (n = 4)	**1.62**	**3.58**	**18.97**	**58.64**	**3.09**	**0.69**	**4.84**	**1.47**	**1.05**	**9.16**
	σ	0.05	0.27	0.44	1.65	0.15	0.60	0.17	0.17	0.08	0.40
Fabric 2a											
8	Gubbacka	0.58	1.20	11.18	75.90	6.79	1.07	3.06	0.73	0.73	5.56
10	Gubbacka	0.63	1.38	12.82	73.27	5.72	0.75	3.49	0.90	0.80	5.97
19	Tallinn	0.78	1.68	14.49	70.58	4.87	0.37	3.77	1.71	0.71	5.90
26	Turku	0.70	1.84	15.80	69.97	4.43	0.27	3.55	0.95	0.75	6.18
16	Tallinn	0.71	1.43	13.84	72.25	5.22	0.48	3.31	1.65	0.89	5.44
24	Turku	0.82	1.70	13.07	72.81	5.57	0.82	3.55	1.31	0.61	5.32
23	Turku	0.78	1.87	15.37	69.53	4.52	0.31	3.84	0.83	0.90	6.57
18	Tallinn	1.01	1.87	13.80	71.03	5.15	1.08	2.86	3.21	0.69	4.45
6	Gubbacka	0.71	2.01	16.12	66.51	4.13	0.58	3.97	1.37	0.98	7.75
	μ (n = 9)	**0.75**	**1.66**	**14.05**	**71.32**	**5.15**	**0.64**	**3.49**	**1.41**	**0.78**	**5.90**
	σ	0.12	0.27	1.59	2.66	0.81	0.31	0.36	0.76	0.12	0.92
Fabric 2b											
1	Gubbacka	0.71	1.83	16.58	67.23	4.06	0.55	3.89	0.78	0.89	7.53
4	Gubbacka	0.77	1.74	17.38	63.57	3.66	1.33	4.01	0.83	1.05	9.32
2	Gubbacka	0.66	1.74	17.12	62.43	3.65	1.23	3.94	1.11	1.21	10.57
14	Mankby	1.41	2.70	16.37	63.79	3.90	0.98	4.98	1.26	0.83	7.69
17	Tallinn	0.75	1.77	13.99	69.19	4.95	0.44	3.56	2.15	1.19	6.96
9	Gubbacka	0.63	1.32	15.35	63.10	4.11	4.76	3.58	1.49	0.87	8.90
20	Tallinn	0.77	1.85	13.83	71.00	5.13	0.50	3.57	1.52	0.90	6.05
25	Turku	0.85	1.82	14.90	66.96	4.49	0.39	3.42	5.02	0.79	5.85
5	Gubbacka	1.09	1.84	14.22	69.14	4.86	0.43	3.34	1.25	0.93	7.77
	μ (n = 9)	**0.85**	**1.85**	**15.53**	**66.27**	**4.31**	**1.18**	**3.81**	**1.71**	**0.96**	**7.85**
	σ	0.25	0.36	1.38	3.14	0.57	1.39	0.50	1.31	0.15	1.53
Fabric 3											
21	Tallinn	1.32	2.87	18.00	61.84	3.44	0.40	4.50	1.38	0.98	8.71

to the SEM analyses, the ceramic cross-sections were examined under a stereomicroscope (Leica M80, Fig. 4) to facilitate visual identification of surface layers, inclusions and voids in the fabrics. For elemental analysis of ceramic pastes, mineral grains and glazes, the SEM was equipped with an Oxford Instruments 350 INCA energy-dispersive X-ray microanalysis system (SEM-EDS) under the following conditions: working distance 15 mm; accelerating voltage 20 kV; process time 5, equivalent of detector deadtime ca. 30%; time of acquisition 180 s.

The reported elemental concentrations of ceramic pastes (Table 3) are mean values of 3–5 SEM-EDS measurements of 250 × 250 μm sized areas (equivalent to an image of the body area at 500 × magnification), selected by avoiding large mineral particles that were probed separately. The reported elements for the ceramic pastes are Na_2O, MgO, Al_2O_3, SiO_2, P_2O_3, K_2O, CaO, TiO_2 and FeO; other concentrations below 0.5 wt % were below the detection limit of the SEM-EDS instrument. The measurements were checked for consistency, recalculated by stoichiometry as oxides using Oxford INCA software and reported as average weight percent values of oxides. For the glaze compositions (Table 4), 3–5 results were acquired by measuring areas of varying sizes, avoiding unfused grains, glaze surface and glaze-body interface areas. The data precision and accuracy tests from the time of the SEM-EDS analyses are reported in Holmqvist et al. 2018 (relative variation co-efficients in precision tests < 10% or < 20%; relative errors in accuracy tests < 10% or < 20% for all oxides). Individual mineral grains in glazes and ceramic bodies were probed separately, and the grain size and frequency, glaze thickness and microstructure, and the estimation of the vitrification stage of both glazes and ceramic bodies as indicators of firing temperatures were evaluated in microstructural analyses (see Holmqvist, 2019: 105–107 and references therein).

4. Results and discussion

4.1. Ceramic fabric groups based on ED-XRF and SEM-EDS data

The cluster analysis dendrogram of the ED-XRF ceramic data (Fig. 5) shows two main branches and their subgroups (Fabrics 1a–b and 2a–b in Fig. 5, Table 2). Similar data patterns are shown in the PCA plots of the ED-XRF data (Fig. 6a–b). Fabric group 1 is dominated by artefacts (11

Table 4
SEM-EDS measured glaze chemical composition and glaze thickness (t, in μm), order and group assignments by CA dendrogram. All analyses normalized to 100%.

No	Date	Site	t (μm)	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	K_2O (%)	CaO (%)	FeO (%)	SnO (%)	PbO (%)
Fabric 1a												
33	1550–1650	Mårtensby	150–180	0.19	0.10	1.84	31.84	0.28	0.53	0.88		64.33
34	1550–1650	Mårtensby	180	0.27	0.10	2.77	30.11	0.21	0.17	1.25		65.13
15	16th c?	Mankby	100	0.41	0.81	4.18	27.59	0.75	0.74	4.09	7.41	54.02
27	1750–1800	Turku	180	0.75	0.74	6.07	35.83	1.16	2.33	3.62		49.49
11	1450–1550	Mankby	180	0.46	0.89	6.00	29.78	0.90	0.70	2.77		58.51
Fabric 1b												
31	17th c.?	Mårtensby	150	1.15	1.68	11.71	40.75	2.95	0.71	5.20		35.85
Fabric 2a												
8	Early 16th c.	Gubbacka	80–100	0.26	0.90	4.92	32.82	0.59	0.65	2.89		56.96
10	Early 16th c.	Gubbacka	40–60	0.22	0.57	4.61	33.31	0.58	0.69	3.49		56.53
19	Late 14th–early 15th	Tallinn	80–100	0.28	1.01	6.87	38.59	0.89	0.92	3.55		47.90
26	1550–1650	Turku	100–180	0.06	0.51	3.64	33.16	0.42	0.45	2.43		59.33
16	Late 14th–early 15th	Tallinn	100–200	0.44	0.69	6.63	34.64	0.59	3.66	2.17		51.17
24	Late 15th c.	Turku	100–180	0.43	0.86	5.34	33.36	0.75	0.36	1.91		56.98
23	Late 15th c.	Turku	100	0.33	0.94	6.26	39.89	1.23	0.39	2.70		48.26
18	Late 14th–early 15th c.	Tallinn	80		0.46	6.95	33.63	0.22	2.23	0.74		55.83
6	1450–1600	Gubbacka	100	0.41	0.81	7.89	47.26	1.65	0.98	2.97		38.03
Fabric 2b												
1	16th c.	Gubbacka	200	0.39	0.26	2.77	27.14	0.31	0.33	4.16		64.90
4	16th c.	Gubbacka	200	0.21	0.63	4.73	27.82	0.50	0.35	2.11		63.79
2	c. 1450–1600	Gubbacka	200	0.06	0.51	3.51	27.29	0.31	0.59	0.78		67.17
17	Late 14th–early 15th c.	Tallinn	100	0.56	0.75	9.73	56.62	3.06	1.00	2.65		25.63
9	15th c.	Gubbacka	60–80	0.17	0.93	4.81	23.99	0.46	0.72	2.27		66.66
20	Late 14th–early 15th c.	Tallinn	40	0.06	1.28	7.07	36.70	0.50	1.63	3.25		49.50
25	16th	Turku	200	0.46	0.44	4.63	42.06	1.14	1.52	2.04		47.70
5	1450–1600	Gubbacka	300	0.29	0.70	4.92	40.74	0.93	0.97	2.29		49.09
Fabric 3												
21	Late 14th–early 15th c.	Tallinn	200–250	2.57	1.32	2.10	32.44	2.86	2.82	2.57		53.32

unglazed, six glazed) found from the four Finnish sites, with one additional unglazed pot found in Tallinn (no. 22). The ceramics in Fabric 1 are made of non-calcareous (CaO < 2.2 wt%), relatively high alumina and iron clays (Al_2O_3 = ca. 16–18, Fe_2O_3 = 5.3–9.5 wt%; see Fig. 7a). This group includes coarse unglazed sherds (nos. 3, 7, 32), i.e. suspected "local ware" of Gubbacka and Mårtensby, 4/5 samples chosen from Mankby, and the Turku samples associated with production waste (nos. 27–30). In addition, both of the clay daub samples from the Gubbacka furnaces (nos. 35–36) belong to Fabric 1a. The glazed sherds in Fabric 1 can be dated from the 16th to the 18th centuries, whereas the unglazed sherds show a wide chronological range, possibly starting from the late Iron Age (no. 32) and continuing until ca. 1800 CE (no. 27).

Fabric groups 2a and 2b include a total of 18 pots, all with glazed surfaces, found in Tallinn (five), Gubbacka (eight), Turku (four) and Mankby (one). Compared to Fabric 1, the Fabric 2 ceramics are similarly non-calcareous (CaO < 4.3 wt%), but display significantly lower Al_2O_3 values (ca. 12–14 wt%), and higher silica content (above 70 wt% on average). Although Fabrics 1 and 2 are clearly geologically related, there are minor differences in certain trace elemental concentrations, e.g. ZrO_2 at ca. 280–430 ppm and Rb_2O at ca. 90–130 ppm, compared to Fabric 1 values of 180–400 and 110–170 ppm, respectively. The Fabric 2 samples are glazed pots dated from the late 14th to the 16th centuries, thus this fabric group is chronologically and typo-morphologically more coherent than Fabric 1. This group contains all but one of the pots analysed from Tallinn, and the floor tile, no. 18.

The cupel (no. 21) found in Tallinn is a clear outlier in the ED-XRF data set (see Fabric 3 in Figs. 5 and 6), with high Fe_2O_3, Rb_2O, SrO, ZrO_2 and BaO values (Table 2), some of which may be use-derived contamination or indication of its status as an import.

The fabric assignments of the pots by ED-XRF were confirmed by micro-chemical SEM-EDS analysis of grain-free ceramic paste/matrix areas indicative of "pre-temper" clay chemistry, linked to the original clay source composition (see Holmqvist et al., 2018 and references therein). The SEM-EDS shows a similar data structure (Fig. 7a–b), indicating that the fabric groups represent different clay sources. The SEM-EDS results also confirm that the ceramics were made of non-calcareous clays (Table 3), with Fabric 1 artefacts (excluding daub samples nos. 35–36) displaying lower silica–alumina ratios (≤4.0) and a higher range of MgO content (1.8–4 wt%) than Fabric 2 pots (SiO2 / Al2O3 = 3.7–6.8; MgO = 1.3–2.7 wt%, Fig. 7b).

In microstructural examination under SEM, the Fabric 1 pots showed relatively well-sorted grain-size (excluding the heterogeneous daub material of nos. 35–36) with generously applied sand-temper characterized by sub-angular-shaped quartz, plagioclase and K-feldspars sized < 600 μm. Sample nos. 22, 27, 28, 30, 31, 33 and 34 also show large voids indicative of the use of organic temper. The mineralogy of the Fabric 1 pots also included frequent biotite mica (< 200 μm), and rare titanite, ilmenite, apatite, rutile, garnet-group minerals, zircon and iron oxides (< 100 μm) as natural clay inclusions. The Fabric 2 samples show similarly applied coarse sand-temper, and largely the same mineralogy as Fabric 1, but higher occurrence of rutile and iron oxides in the clay fraction, and only two porous samples (nos. 23–24) with large voids. Fabric 3 sample no. 21 (ceramic cupel) displays similar general mineralogical characteristics, but excludes apatite, rutile, or garnet-group minerals.

The vitrification stage of the clay minerals indicative of the firing temperatures of the pots was estimated in all of the samples under SEM using high magnification (1000x) secondary electron (SE) topographic images (Fig. 8a) to evaluate the level of sintering and glassiness of the fabrics. The samples showed no signs of vitrification of the paste minerals, or very early development of vitrification, suggesting that the firing temperatures remained below or at 800 °C (Bland et al., 2017; Holmqvist, 2019: 105–107).

The first fabric group is dominated by pots found at the four Finnish sites, notably representing a wide chronological range (possibly from the late Iron Age to ca. 1800 CE). Fabric 1 includes stylistically and morphologically varied artefacts, glazed and unglazed pots, kiln wasters from Turku, and structural ceramics sampled from Gubbacka as "local" ceramic material – these factors strongly link the Fabric 1 pots with the northern side of the Gulf of Finland, i.e. origin in what is now Finland. This diverse group probably contains objects made in different times and places. The kiln wasters are of Turku origin, and the same possibly applies to glazed pots from Mankby and Mårtensby in this group, although the glazed redwares may have been made in the Helsinki region as well,

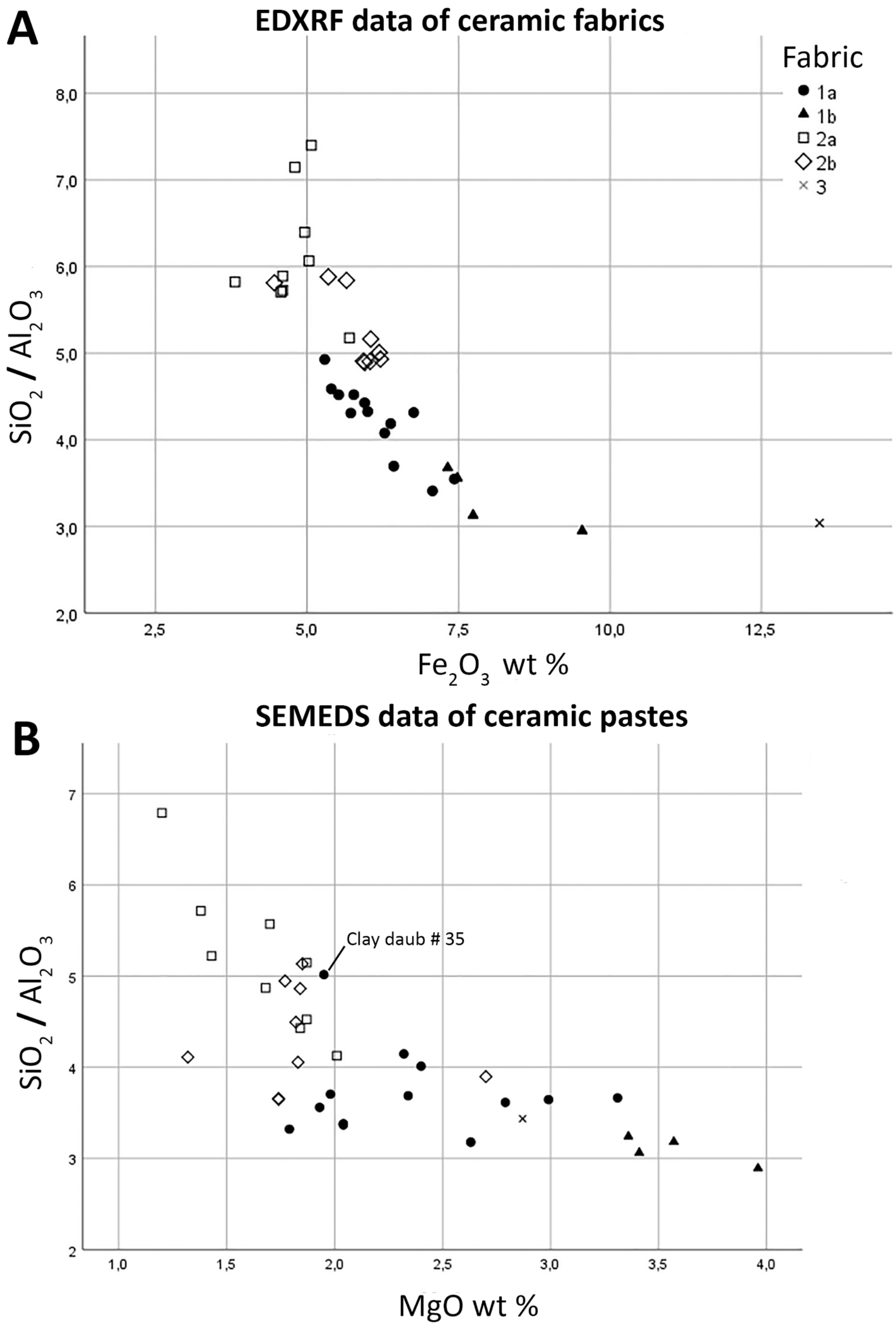

Fig. 7. a) A scatter plot showing the ED-XRF data silica/alumina ratio vs iron content in the ceramic fabrics, b) SEM-EDS measured silica/alumina ratio vs MgO content of ceramic pastes; samples marked by CA groupings.

especially in the 16th–17th centuries (cf. the dates of the glazed Mårtensby pots in this group). Turku and Helsinki are on the Finnish coast, only ca. 150 km apart, so pots from these geologically related localities can be difficult to differentiate based on the geochemical data (see e.g. Korsman and Koistinen, 1998: 95–97; Al-Ani and Sarapää, 2008: 82). Redware manufacture was positively established in Turku at the turn of the 16th and 17th centuries, if not earlier (Pihlman, 1989; Wahlberg, 2000; Tulkki, 2003). Nevertheless, the unglazed coarseware pots from Gubbacka, Mankby and Mårtensby were almost certainly produced in the greater Helsinki area, e.g. in local village workshops.

One of the Tallinn pots (presumably late 13th c. context) belongs to this otherwise Finnish-find dominated group, yet its chemical profile in both the ED-XRF and SEM-EDS data fits very well in this group. Its tentative status as a Finnish import is supported by its unusual size and shape compared to typical Tallinn finds. The late 13th century date is rather early to suggest redware export from Finland; however, we can speculate that this unglazed pot was produced by Swedish settlers on the Finnish coast, and traded to Tallinn along with other transactions.

In contrast to the typo-chronologically varied Fabric 1 linked with the Finnish-coast origin, the other main group, Fabric 2, includes only glazed sherds dated from the late 14th to the 16th centuries, but the pottery was found at four sites – Tallinn, Gubbacka, Mankby and Turku – suggesting that Fabric 2 products were widely distributed. Although this group includes all the glazed pots and the glazed tile from Tallinn, we cannot with certainty conclude that these are Tallinn manufacture, especially considering that there is no direct archaeological evidence of redware manufacture in Tallinn. Some of the Fabric 2 pots show visual resemblance to Southern Scandinavian redwares, and this factor,

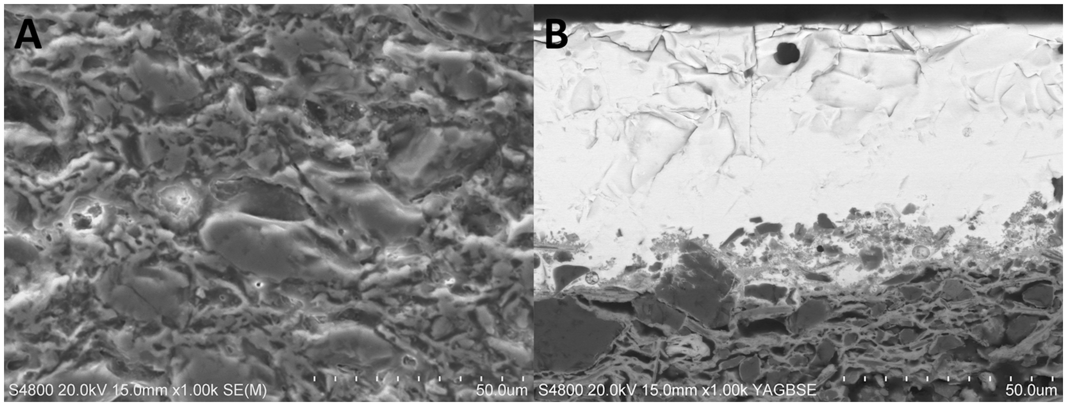

Fig 8. a) SEM-SE micrograph of ceramic paste of sample no. 25 with early vitrification development; b) SEM-BSE backscatter micrograph of sample no. 26 showing crystallization on the glaze-ceramic fabric interface.

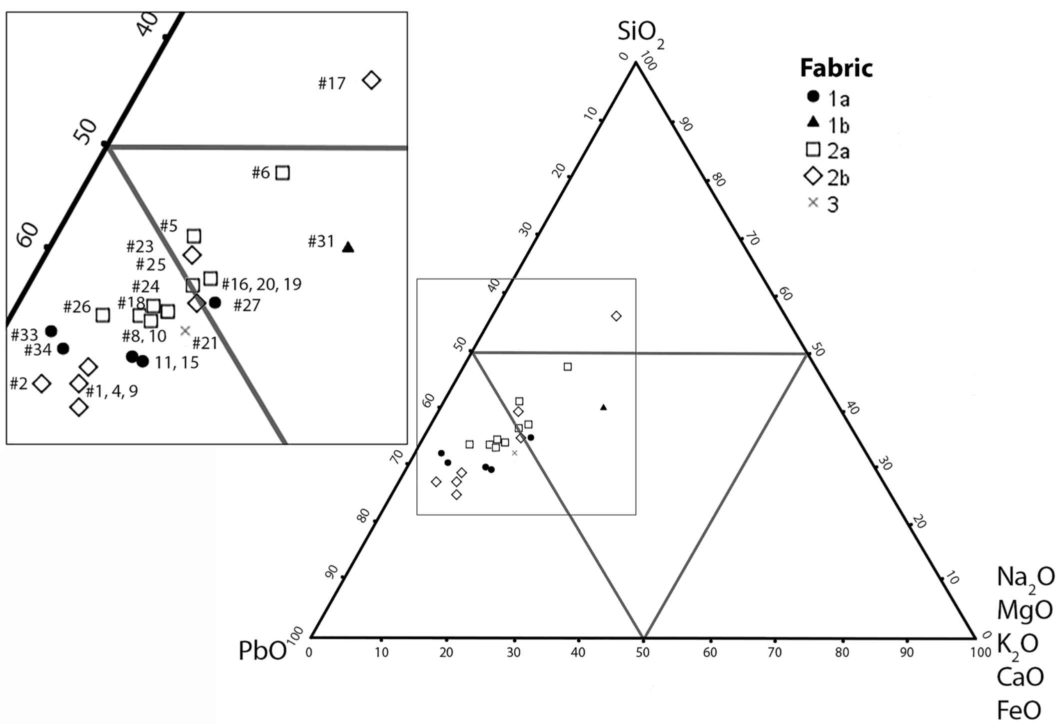

Fig. 9. A ternary diagram of the SEM-EDS measured glaze compositions. Concentrations are normalized to 100% (the tin oxide concentration of tin-opacified sample no. 15 is excluded).

combined with the close geochemical similarity to Fabric 1 pots (made on the northern Gulf of Finland), may be evidence that Fabric 2 ceramics were made in Tallinn by immigrant potters, who also produced pots for export.

It is apparent from the ED-XRF and SEM-EDS fabric/paste data that the clays used to manufacture Fabric 1 and 2 pots are geologically associated, probably from the Gulf of Finland environment. Alternative interpretations can also be made regarding the source areas of the two fabric groups. The limited geochemical and mineralogical variation between Fabrics 1 and 2 could imply that they represent alternative ceramic recipes originating from the same geological area (modern Estonia, eastern Sweden, or even the Low Countries?) yet a closer inspection of the sample distribution in these groups complicates this scenario. Relative similarity between fabric groups can be expected from local products of sites located within ca. 180 km from each other (Fig. 1), especially considering the geological (petrological and geochemical) similarities between southern Finland (and the Helsinki region, in particular), and the structural-petrological zone of Tallinn in Northern Estonia (Soesoo et al., 2004; 2020; Kähkönen, 2005).

4.2. Glaze composition and application

Of the 34 analysed ceramic sherds, 24 had glaze coating or at least glaze spots on their surface(s) (Table 1, Fig. 8b). The glaze was usually applied to the interior and over the edge of the rim, and in some cases to the exterior of the pot (Figs. 2–3). On visual inspection, the glazes appear transparent, often yellow hued (Figs. 2–3, 4a, c–d). In the SEM-EDS data on the glazes (Table 4, Fig. 9), no signs of colourants were detected. It is probable that the yellowish hue derives from iron-absorption from the Fe-rich ceramic fabrics (see Molera et al., 1997: 29). The majority of the analysed glazes are high lead glazes (defined as containing 45–60% PbO by Tite et al. 1998), and only three pots (nos. 6, 17, 31) have glazes with PbO content < 45 wt%. The main components in the glazes are lead oxide (PbO ca. 25–67 wt%), silica (SiO_2 ca. 24–56

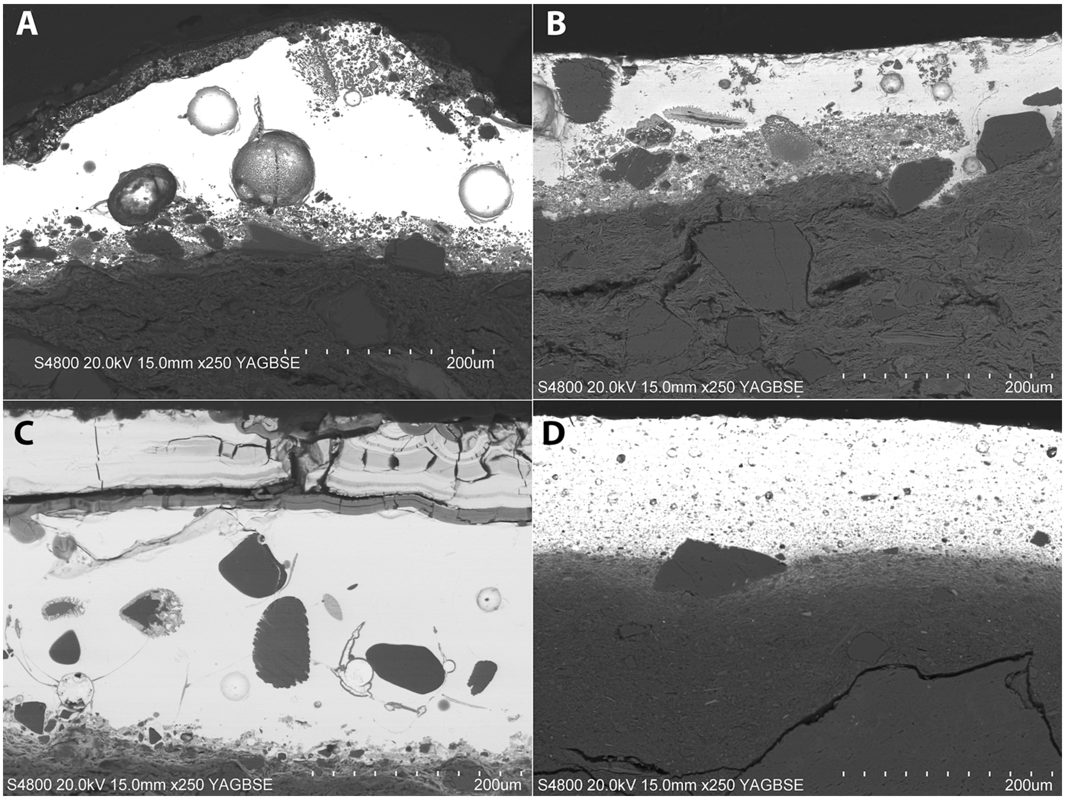

Fig. 10. SEM-BSE micrographs of Fabric 1 pots with varied glaze thicknesses: a) tin–lead-glazed sample no. 15; b) no. 27; c) no. 33; d) no. 31; showing uneven glazing (a); bubbles, cracks and undiffused mineral grains, and crystallized fabric-glaze interfaces (a–d); and post-depositional deterioration (c). The well-sorted grain size and sand-temper are visible in the ceramic fabric of no. 31 (d).

wt%), and Al_2O_3 (1.8–11.7 wt%), with MgO, K_2O, CaO and FeO (Table 4). Other components do not exceed the 0.5 wt% detection limit of the SEM-EDS.

Pot no. 15 found in Mankby has a tin–lead glaze applied on its interior (Table 4), with a typical tin content of ca. 7 wt% (see Tite et al., 1998: 244; Mason and Tite, 1997), but the glaze still has a high lead content (PbO = 54 wt%, Fig. 9). The interior glaze of this 16th-century sherd (Fabric 1a) shows opacity with more brownish/yellowish colour than the transparent lead glazes (Figs. 2, 4c), but both surfaces of this sherd are weathered and the glaze is poorly preserved. Tin-opacified glazes were manufactured e.g. in the Low Countries from the early 16th century onwards (see Mason and Tite, 1997; Carlsson et al., 2018), but this 16th-century sherd provides no geochemical indication of imported status, thus it is possible that tin–lead glazes were produced in the Finnish region at this time.

The glaze thicknesses (Table 4) vary significantly between the studied samples, and many pots present glazes with very uneven surfaces, gas bubbles, cracks and abundant (partly or completely undiffused) mineral grains, undissolved in the firing process (Figs. 10 and 11). The grains, fairly large in relation to the glaze thickness, often crack the glaze surface (Fig. 11a, c). These features are characteristic of short firing times, low temperatures and unstandardized glazing technologies, starting from the mixture preparation.

High-lead glazes in general have low firing temperatures (700–1000 °C, see Hurst and Freestone, 1996: 16; Tite et al., 1998), but the only partly melted glazes analysed here imply inadequate firing temperatures and times, and firing temperatures below 750 °C leaving grains undissolved (Molera et al., 2001: 1121). Undiffused, silica-rich areas in a glaze reduce its transparency affecting its visual appearance, and can also cause flaking (Tite et al., 1998; al-Saad, 2002: 805). As a result, the glazes often show weathered exteriors deriving from use wear or post-depositional damage.

The cupel sample, no. 21 (Fabric 3), shows a glassy matrix filled with abundant partially melted K-feldspars on its surface (Fig. 11f). The cupels were made without coating, thus the glassy surface here derives from the process of bead making at the Sulevimägi 4/6 site. There are no painted patterns visible under the glaze surfaces, and the lead diffusing into the ceramic fabrics also prevents confirmation of a slip layer applied below the glaze under SEM (see Pérez-Arantegui and Castillo, 2000; Krishnan et al., 2005).

The sampled pots systematically present crystals in the glaze-ceramic fabric interface (Fig. 8b, 10–11) deriving from ceramic fabric reacting with the glaze mixture during firing, creating chemical diffusion between the coating and fabric (Molera et al., 2001; De Benedetto et al., 2004: 618). The crystal phase is characteristic of glazes applied on unfired ceramic surfaces. This undesired effect reduces the transparency of the glaze, and can be minimized by optimizing the glaze mixture (eutectic glaze containing ca. 32% silica, 61% lead oxide and 7% alumina, see Tite et al., 1998: 251, 253). There is significant variation in glaze compositions within the ceramic fabric groups (Table 4), suggesting that different high-lead mixture glazes were applied.

We also examined whether the high-lead glazes were applied as lead oxide itself, reacting with the clay body during firing (in which case, the major oxide values of the glaze would match those of the clay body after subtraction of the lead concentration and re-normalization) – or as a lead-silica mixture (dissimilar to the clay body chemistry unless the same clay was used in the glaze mixture; see Tite et al., 1998: 249–249; Walton and Tite, 2010: 748–749; Palamara et al., 2016: 144–145). The bi-plots (Fig. 12a–d) of the major oxide concentrations of the glazes (after subtraction of the lead concentration and re-normalization) versus those of the clay bodies show that the data of samples 8, 16 and 20 fall on the unity line, suggesting that for these pots, lead oxide itself was applied to produce the glaze. This may also apply to sample nos. 19, 24, and 31, plotting close to the unity line. In these cases, the relict mineral

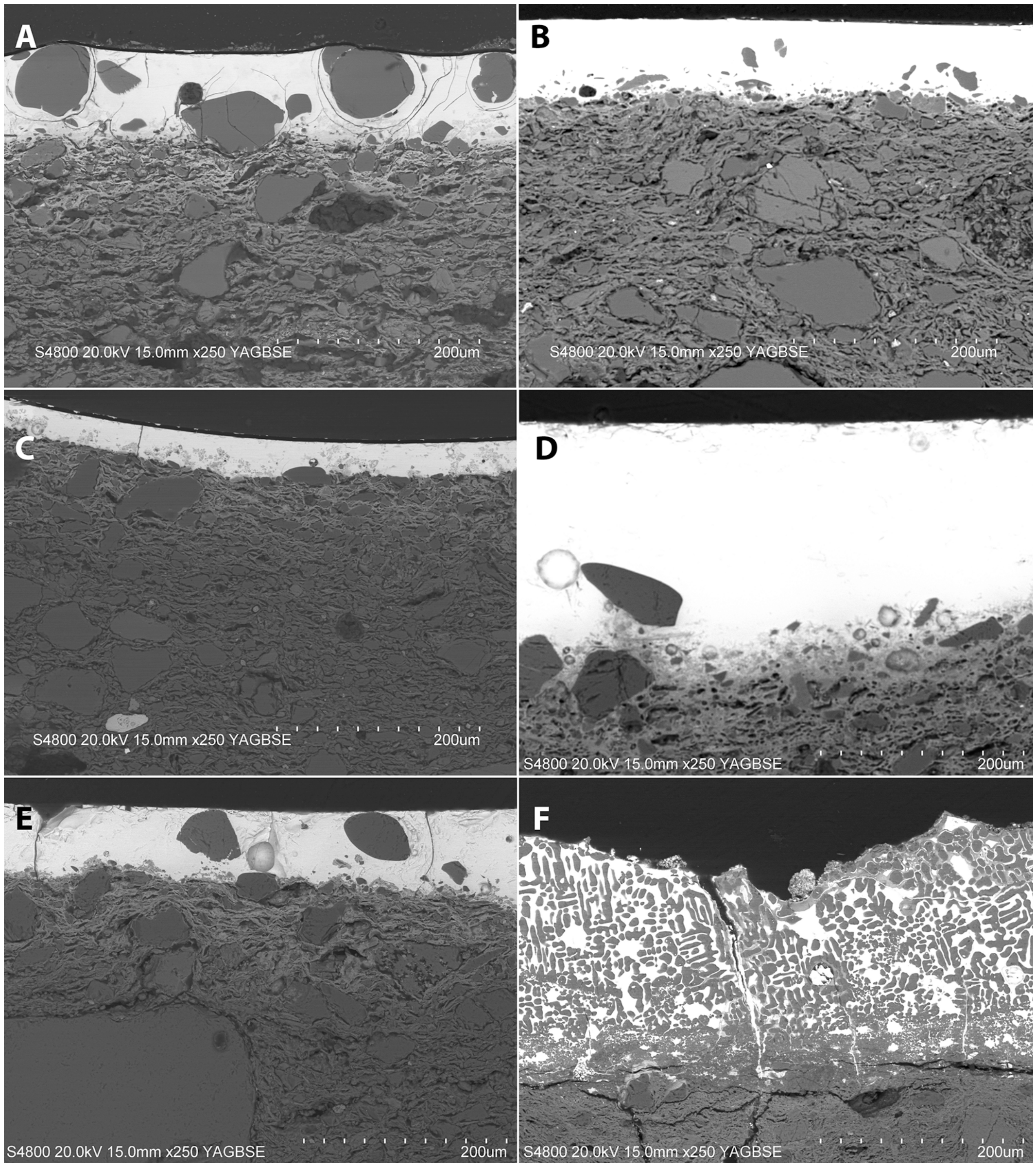

Fig. 11. SEM-BSE micrographs of Fabric 2 glazes, showing different glaze thicknesses, bubbles, cracks and undiffused mineral grains, and crystallized glaze-fabric interfaces: a) sample no. 6; b) no. 17; c) no. 20; d) 25; e) 26; f) no. 21 (cupel).

grains in the glazes may, in fact, derive from the body-glaze reaction. Apart from no. 31 (being a 17th c. pot of Fabric 1b), pots 8, 16, 19, 20, and 24 date from the mid-14th to the early 16th century and belong to Fabric 2 subgroups, associated with Tallinn origin. For the rest of the pots, the glaze and body compositions appear non-related (Fig. 12), and a *lead-oxide-plus-sand* mixture was applied instead.

To conclude, varied glaze compositions and application techniques are attested in our sample material. It is apparent from the poor physical quality of the glazes that the pots were not successfully fired, and the recurrent uneven glaze surfaces and heterogeneous glaze matrices, with relict grains, bubbles and cracks, are not indicative of consistent application practices or high-standard glazes (i.e. fully vitrified, glassy matrices). Perhaps the potters did not aim to produce high-standard glazes for these modest pots, or did not possess the skills or recipes for quality glaze making.

5. Conclusions

The results of the ED-XRF and SEM-EDS analyses of 34 redware objects from five late medieval sites in modern Finland and Estonia, the hamlets Gubbacka, Mankby, Mårtensby and the towns Turku and Tallinn, revealed two main compositional ceramic fabric groups, one of which indicating redware manufacture in the Helsinki region and Turku, and the other in Tallinn.

Based on the micro-chemical and structural characteristics, the artefacts were manufactured by applying high-lead-content (PbO < 67 wt %) glazes on non-calcareous ceramic fabrics prior to firing. The combination of high-lead glazes with non-calcareous ceramics was invented already in the 9th–12th century Byzantium with many technological benefits – high-lead glazes require lower firing temperatures than alkali-glazes, and are less dependent on the ceramic fabric quality, as their thermal expansion coefficient is close to that of coarse ceramics (Tite et al., 1998: 242–253; Walton and Tite, 2010: 754). One of the pots also had a tin-opacified glaze. In most cases, the glaze was made by mixing lead oxide with sand (undissolved quartz and feldspar grains), but sometimes (particularly in the Tallinn group) a lead compound itself was used. The chosen firing times and temperatures were inadequate to create glassy coatings, leaving the glazes cracked, filled with grains and

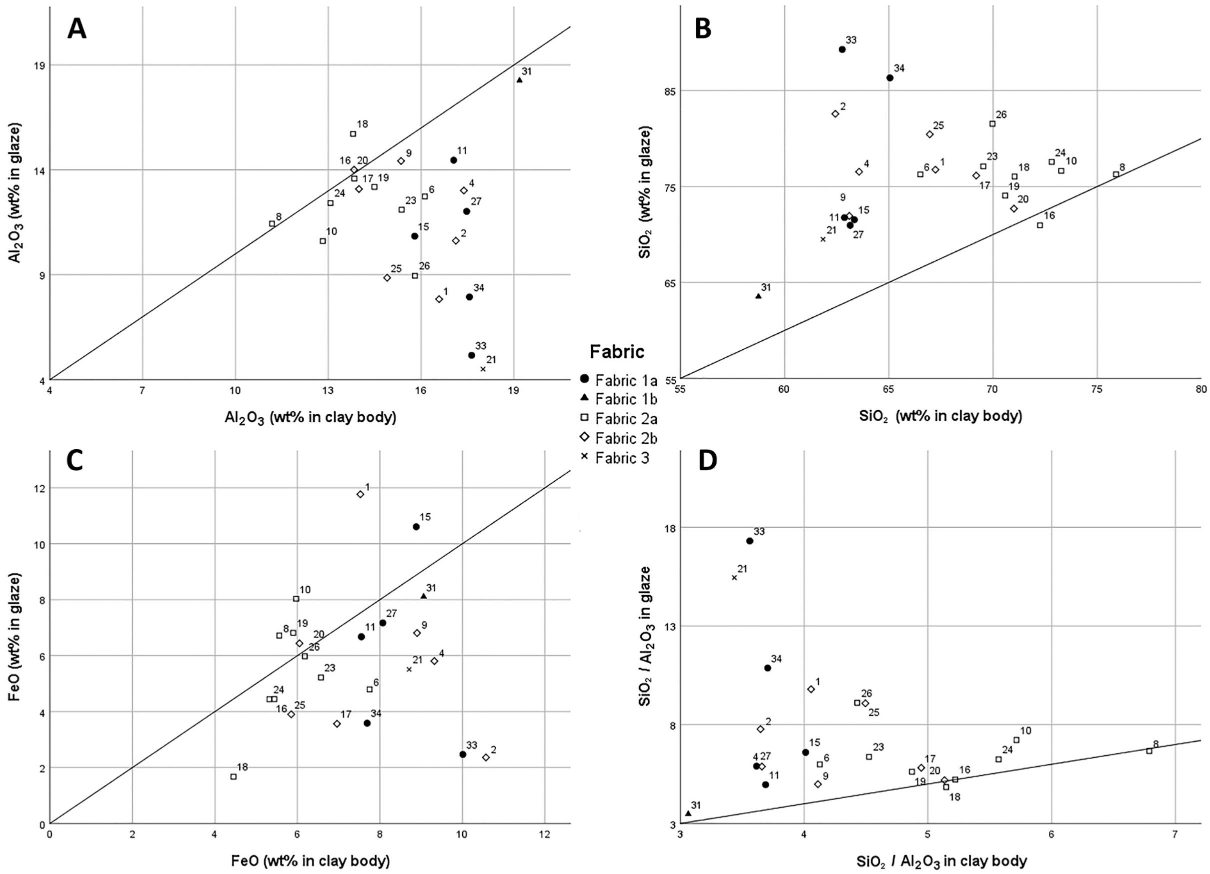

Fig. 12. a–d. Bi-plots of SEM-EDS measured Al_2O_3, SiO_2, and FeO concentrations, and SiO_2/Al_2O_3 ratios of the clay bodies and glazes (after subtraction of the lead concentration and re-normalisation). The data points falling on the unity line indicate that the glaze was applied as lead oxide, whereas in other cases a lead-oxide-plus-sand mixture was used.

bubbles, and probably jeopardized the impermeability, hardness and the appearance of the coatings.

Perhaps surprisingly, the analysis did not reveal clear compositional indications of pottery imported from outside the sample region, that is, geochemical outliers that could be interpreted as imports from the Low Countries, eastern Sweden or Germany, all of which are known redware distributors. However, we are discussing ceramic provenance of a fairly small sample set, faced with the lack of reference data, and dealing with artefacts from a period when redware pots were manufactured “almost everywhere” by mobile craftsmen, small-scale rural and urban producers, single producers with multiple recipes and forms in their repertoires, coupled with the potential international impact of Hanseatic trade (see Carlsson et al., 2018).

In any case, the dominance of redware pots in late medieval contexts in Finland demonstrates that redwares were very much in vogue not only in continental Europe and Scandinavia, but also around the Gulf of Finland, prompting diverse local manufacture of these desired products. The earliest glazed pots found at the Finnish sites are imports, predating the “local” glazed pots, hence local potters may have been adapting to the new glazing technology as a response to these imports. Thereafter, the lead-glazing practice was continued in the local craftsmanship for centuries.

Our ceramic samples were prepared as polished cross-sections and subjected to both ED-XRF and SEM-EDS analyses. While this approach may have compromised analytical accuracy and sample representation compared to quantitative analysis using homogenized samples, it was necessary to control elemental migration from the high-lead glazes into the ceramic fabrics, which would have largely prevented accurate geochemical characterisation in bulk analyses. Furthermore, phase-analyses under SEM provide technological data on both ceramic and glaze manufacture that are inseparable characteristics of the late medieval redware pottery technologies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2020.102627.

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