

Bow and 'A'-marked porcelain: a tangible link from the Stratford (East London) factory site

A paper by J Victor Owen and Nicholas G Panes read by J Victor Owen at the Museum of London Archaeology, Mortimer Wheeler House, London N1 on 10th March 2012

Introduction

In 2006 Museum of London archaeologists excavating the Stratford (East London) site of the Bow porcelain manufactory unearthed a glazed but unmarked and undecorated white teapot lid. (1) Anton Gabszewicz noticed a strong resemblance between this artifact and the lid on an A-marked teapot in the collection of the Victoria and Albert Museum. (1 inset) To test the hypothesis that the excavated teapot lid does indeed correspond to A-marked porcelain, the Museum of London kindly authorized the removal of a small piece of the lid for chemical analysis. In addition, four porcelain sherds found on the site were analysed.

Sample description

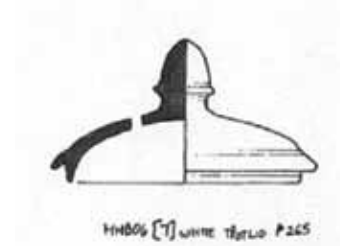
The excavated teapot lid (1) is dome-shaped with a break in curve near its edge, an acorn-shaped finial,

and a well-defined 'footrim'. It is about 6 cm in diameter. Its intended use as a teapot lid is indicated by the presence of a small hole.

The lid was found with other ceramic artifacts, including porcelain sherds and kiln furniture, in a waste dump that evidently was established during redevelopment of the Bow site in the 1750s. The four porcelain sherds selected for analysis are white, glazed and undecorated. Two of these samples (P244 and P313) are derived from small cups or teabowls with shapes resembling A-marked porcelain; the others are undistinguished wasters. (2)

Archaeological context

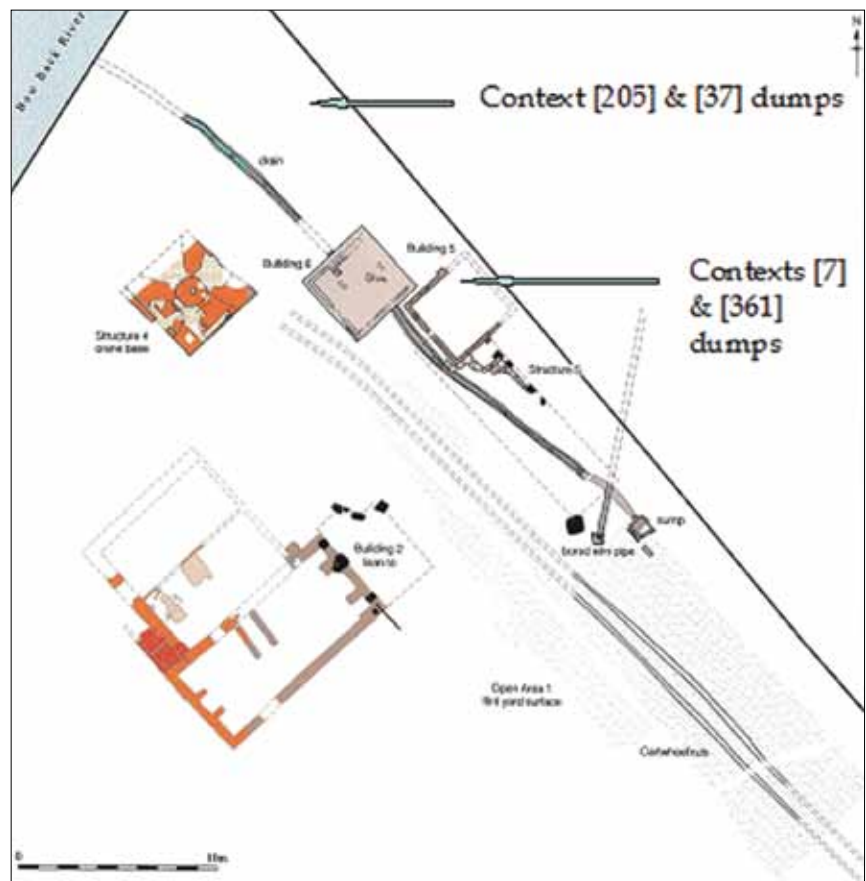
All of the samples were found in what has been referred to as context 7, located to the northeast of the excavated site, which appears to be a waste



1. Photograph of the excavated teapot lid. Insets show a cross-sectional line drawing of the lid, and an A-marked teapot with a lid similar to the excavated artifact. Courtesy of the Victoria and Albert Museum



2. Photograph of four analysed porcelain sherds recovered from the Stratford site waste dump. Courtesy of the Museum of London



3. Plan of the excavation site showing the position of Context 7 waste dump from which the analysed samples described here were recovered. Courtesy of the Museum of London

dump. (3)¹ Although in a highly fragmentary state, context 7 is undoubtedly one of the most important dumps of porcelain waste excavated in 2006. From it some 14,704 sherds (~180 kg) were recovered. Approximately 40% of these sherds are from glazed blue and white wares; another substantial proportion of the wasters comprise plain white glazed wares. It is from the latter that the samples described here were selected for analysis.

Blue and white and plain white glazed porcelain dominate the assemblage; unglazed biscuit ware accounts for only 12.5% of all sherds. In addition, there are a small number of biscuit sherds with painted decoration that has been hardened on but not fired. In contrast, other excavated waster dumps on the site chiefly consisted of biscuit wares, with relatively small proportions of finished glazed ware of any kind. In this respect, context 7 is exceptional, and probably represents the large-scale dumping of imperfect finished ware from several firings. On stylistic grounds it appears that most wasters date to the 1750s.

Analytical methods

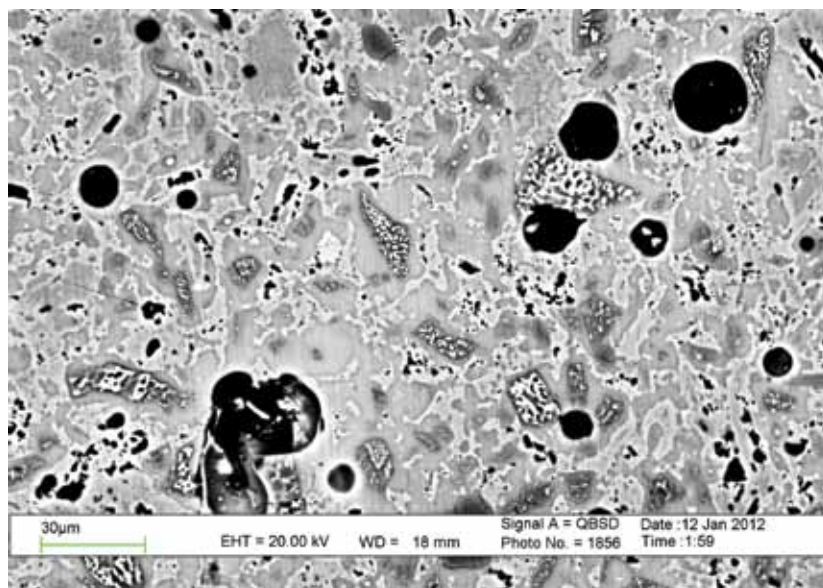
The teapot lid and four porcelain sherds were analysed using a JEOL Superprobe 8200 electron probe microanalyser equipped with four wavelength dispersive spectrometers. In addition, the lid was re-

analysed using a LEO 1450VP scanning electron microscope equipped with a silicon drift detector. Only the microprobe data are reported here, but the full dataset for the teapot lid and details of analytical procedures are reported elsewhere.² The composition of the teapot lid will be described first.

The teapot lid: Mineralogy, microstructure and geochemistry

The excavated lid contains partly resorbed silica polymorphs (probably alpha-quartz), devitrified glass particles (represented by fine-grained intergrowths [symplectites] of silica polymorphs, diopside \pm pseudowollastonite³), and metakaolin patches. (4) The symplectites are mantled by a double corona comprising an inner, siliceous-aluminous layer that is enclosed by an outer, feldspathic rim from which plagioclase microlites extend into metakaolin patches. Unlike the feldspathic rim, the inner corona lacks pores, so has been interpreted as a melt phase.⁴ The concentration of pores in the feldspathic corona (4) strongly suggests that plagioclase formed during cooling below the vitrification temperature (i.e., it is a subsolidus phase). In terms of its mineralogy and microstructure, the excavated lid closely resembles that of a fluted, A-marked cup described by Ian Freestone.⁵

4. Backscattered-electron image showing the mineralogy and microstructure of the excavated teapot lid. The devitrified glass particles (symplectites; mottled white/dark grey grains) are enclosed by an inner corona consisting of a siliceous-aluminous melt phase (medium grey) and an outer feldspathic corona (pale grey) that grows into and replaces metakaolin (medium grey patches studded with pale grey plagioclase microlites [e.g., upper left of image]). Black spots concentrated in the outer coronas are pores.



	Bulk paste	Glaze
SiO ₂	62.8	66.9
TiO ₂	0.0	0.1
Al ₂ O ₃	22.4	12.4
FeO	0.2	0.5
MnO	0.0	0.1
MgO	1.1	1.6
CaO	5.4	11.1
Na ₂ O	3.9	2.7
K ₂ O	3.2	3.2
PbO	0.4	0.4
SnO ₂	0.1	0.5
P ₂ O ₅	0.2	0.4
SO ₃	0.2	0.1
Total	100.0	100.0
n =	47	6

n = number of spot analyses

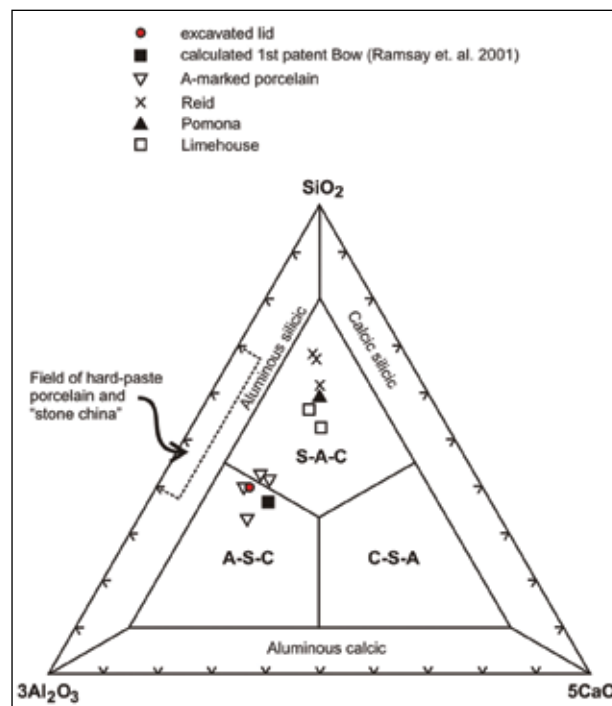
5. Composition of the paste and glaze of the teapot lid excavated from Stratford, East London

The body of the excavated lid has an aluminous (22% Al₂O₃) and siliceous (63% SiO₂) composition, with 5.4% CaO, and similar concentrations of both soda and potash (3.9% Na₂O, 3.2% K₂O). (5) The glaze is also dominated by these components, but has about half the alumina and twice the lime content as the body. Its lead content is negligible (0.4% PbO). The glaze contains traces of tin oxide grains, and has crystallized minute (micron-scale) diopside microlites. Small amounts of tin oxide also occur in the body, either as a deliberate or incidental additive, or, possibly reflecting the recycling of glazed, A-type porcelain wasters as grog (chamotte) in the ceramic paste.⁶

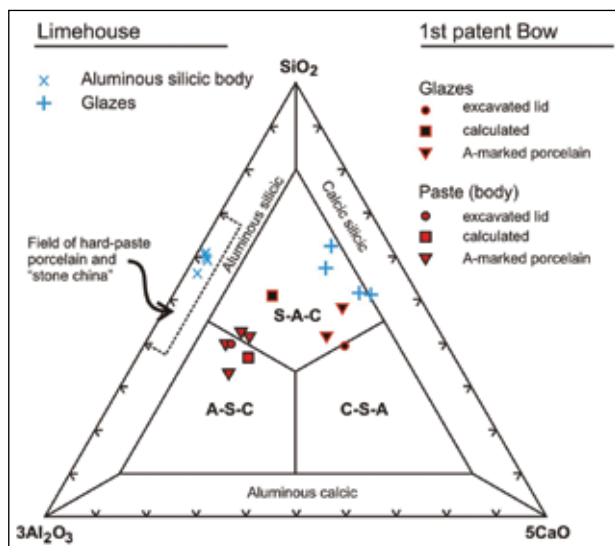
This sample is an aluminum-rich variant of the S-A-C porcelains produced elsewhere (e.g., at the Limehouse⁷, Reid and Pomona factories⁸) in the UK during the 18th century. As a result, analytical data for this sample plot in the A-S-C field on the SiO₂-3Al₂O₃-5CaO diagram (6) used to classify siliceous-aluminous

and S-A-C – type (*sensu lato*) wares.⁹ It plots within a tight cluster of points representing the compositions of A-marked porcelain and the composition of early Bow porcelain reconstructed¹⁰ from Heylyn and Frye's first (1744) patent.

Furthermore, the composition of its high temperature (calcic-aluminous-siliceous) glaze (5, 7) matches that found on A-marked porcelain¹¹, and known to have been produced at Bow in the 1740s, as described in the Heylyn/Frye patent. This glaze contrasts with the lead-rich (low temperature) glazes that characterize contemporary S-A-C wares. The mineralogy, microstructure, and composition of this sample are therefore consistent with documented A-marked porcelain¹², and Heylyn and Frye's 1st patent. Although it is unmarked, we conclude that it corresponds to A-marked porcelain produced by the Bow factory during the 1740s.



6. Comparison of the bulk paste composition of the excavated teapot lid with analysed A-marked porcelain (data from Freestone, 1996; Ramsay and Ramsay, 2007) and early Bow porcelain calculated from Heylyn and Frye's 1st patent (Ramsay et al., 2004), and with the average composition of some contemporary and later S-A-C porcelains (Limehouse: Freestone, 1993; Panes et al., in prep; Reid and Pomona: Owen and Hillis, 2003). Diagram is after Owen (2007)



7. Comparison of the composition of the glaze on the excavated teapot lid with analysed glazes on A-marked porcelain and on aluminous-silicic Limehouse porcelain. A-marked porcelain data are from Freestone (1996), and Ramsay and Ramsay (2007). Limehouse data are from Freestone (1993) and Owen (2000)

Other porcelain sherds: Mineralogy, microstructure and geochemistry

The four analysed porcelain sherds contain two textural and compositional varieties of a calcium phosphate phase(s), silica polymorphs, a subordinate melt phase \pm calcic plagioclase. The phosphates comprise 'stippled' and 'unstippled' variants, a feature common in phosphatic porcelains, including Bow, that appears to indicate differing degrees of heating and recrystallization. The 'stipples' correspond to pores that in some instances host a melt phase. At higher temperature, melt blebs filling these pores can coalesce and leak from the phosphate as it recrystallizes, purging these grains both of pores and melt blebs.¹³

In terms of paste composition, all four sherds are low-sulphur, phosphatic porcelains. They all have similar $\text{CaO}/\text{P}_2\text{O}_5$ ratios (3.3-3.4; molecular proportions). This indicates that no source of calcium (e.g., gypsum) other than bone ash was used in the

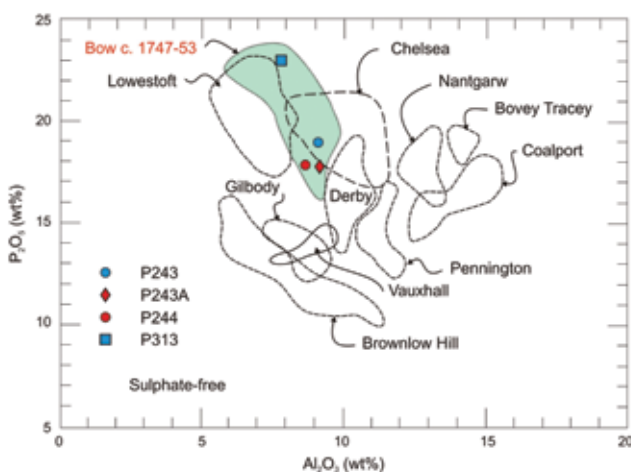
	Pastes				Glazes			
	P243	P243A	P244	P313	P243	P243A	P244	P313
SiO ₂	44.9	46.9	47.6	34.2	38.55	37.53	37.5	41.37
TiO ₂	0.4	0.4	0.4	0.5	0.07	0.1	0.05	0.05
Al ₂ O ₃	9.0	9.1	8.7	7.9	0.96	0.93	1.47	0.1
FeO	0.3	0.3	0.3	0.4	0.07	0.03	0.07	0.05
MnO	0.0	0.0	0.0	0.0	0.01	0.03	0	0
MgO	0.5	0.5	0.5	0.6	0	0	0	0
CaO	24.5	23.6	23.3	30.2	1.81	1.4	1.85	0.8
Na ₂ O	0.6	0.7	0.7	0.9	0.45	0.65	0.61	0.42
K ₂ O	0.6	0.6	0.6	0.8	2.38	2.81	2.23	4.86
P ₂ O ₅	18.9	17.7	17.6	22.8	0.07	0.09	0.23	0.33
PbO	0.0	0.0	0.0	1.3	54.65	56.91	55.42	52.65
SnO ₂	0.0	0.0	0.0	0.0	0	0	0	0
BaO	0.0	0.0	0.0	0.0	0.04	0	0.01	0
Cl	0.0	0.1	0.0	0.1	0.06	0.07	0.07	0.06
SO ₃	0.1	0.1	0.1	0.2	0	0	0.03	0
CoO	0.0	0.0	0.0	0.0	0	0.07	0.04	0.02
Total	100.1	100.0	100.0	100.0	99.1	100.6	99.55	100.7

8. Paste and glaze compositions of phosphatic sherds excavated from Stratford, East London

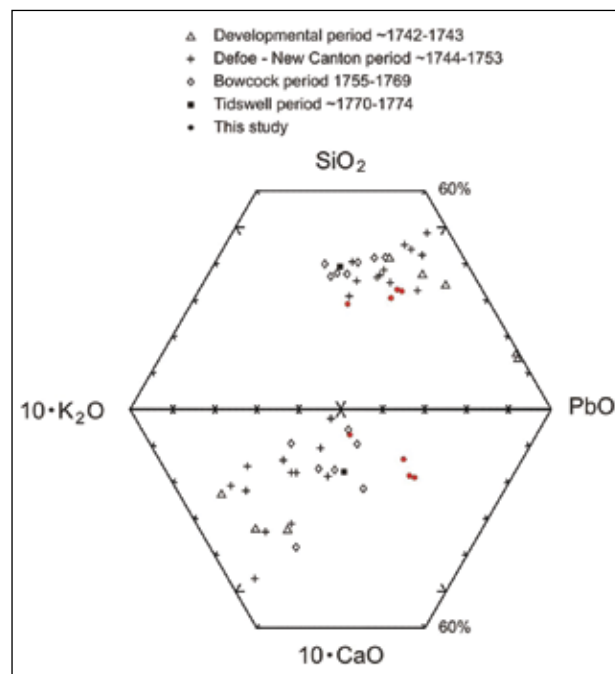
manufacture of these artifacts. This inference is consistent with the very low sulphate content ($\leq 0.1\%$ SO_3) of these samples. Notwithstanding their similar lime/phosphate ratios, one of the samples (P313) is a compositional outlier, having lower silica (34 *versus* 45-48% SiO_2) and alumina (7.9 *versus* 8.7-9.1% Al_2O_3) contents, but a higher concentration of bone ash components (30 *versus* 23-25% CaO ; 23 *versus* 18-19% P_2O_5). (8)

The glaze on P313 is also distinct. It has a lower lead content (53% *versus* 55-57% PbO) than the glaze on the other sherds, and has a higher silica content (41% *versus* $\sim 38\%$ SiO_2), about twice as much potash (4.9% *versus* 2.2-2.8% K_2O) and half as much lime (0.8% *versus* 1.4-1.9% CaO), and negligible alumina.

Despite these compositional contrasts, the paste compositions of all four samples plot in the field for Bow porcelain circa 1747-1753 (per literature data¹⁴) on a phosphate-alumina diagram. (9) This interpretation is substantiated by the glazes where plotted on an SiO_2 -10 K_2O - PbO diagram. (10, top half) The glazes cluster near the field for 'Defoe-New Canton era' glazes.¹⁵ In contrast, given the present analytical database for Bow glazes, lime seems to be a less reliable component for distinguishing different periods of this factory's production history, because the data for documented pieces are relatively scattered



9. Composition of the four excavated phosphatic sherds on a P_2O_5 - Al_2O_3 porcelain-discrimination diagram. Note that all four samples plot in the Bow field for the period 1747-1753



10. Comparison of the composition of the glazes on the four excavated phosphatic sherds on a SiO_2 -10 K_2O - PbO - CaO diagram with Bow glazes (modified after Ramsay and Ramsay, 2011). See text

on an SiO_2 -10 K_2O - CaO plot, and the glazes on three of the four phosphatic sherds reported here plot as outliers on this diagram. (10, bottom half)

Only the glaze on P313 plots among the documentary-porcelain glaze data for this part of (10), and it lies near two Bowcock-era (1755-1769), rather than earlier, glazes. It is unclear whether this indicates that there were few systematic compositional changes in the types of glazes used at Bow over time, or simply indicates difficulties in determining their bulk composition. Glazes tend to be compositionally zoned (i.e., their composition changes from the outside to their inner edge). Moreover, they can contain irregularly distributed, refractory particles, notably tin oxide, that can render difficult the contribution of their components to the bulk compositions of the glaze where determined by microbeam techniques.¹⁶ Finally, recent work¹⁷ has revealed the use of compositionally distinct repair glazes to mask incompletely covering or poorly-fitting (e.g., crazed) glazes. If these features are

not taken into consideration by all analysts working on this medium, then it is not possible to compile suitable glaze data from the literature so that reliable time/composition plots can be established.

Interpretation

In terms of its mineralogy, microstructure, and bulk paste and glaze composition, the excavated teapot lid closely corresponds to published data for analysed A-marked porcelain.¹⁸ Moreover, its paste composition is consistent with the composition of 1st patent Bow porcelain as calculated and reported by Ramsay et al.¹⁹ The same cannot be said, however, for its glaze. Although the composition of the teapot lid glaze plots close to analysed glazes on A-marked porcelain, it is considerably more calcic and less siliceous and aluminous than the high-temperature Bow glaze as calculated by Ramsay et al.²⁰, either because of uncertainties in the actual proportions of ingredients as reported in the 1744 patent, or because Heylyn and Frye deviated from their intended glaze recipe.

It is interesting to note that a similar (albeit more siliceous and less aluminous) glaze was used on aluminous-silicic porcelain produced by the Limehouse factory. (7) This suggests a possible connection between the two enterprises, evidence for which must be sought in archival records.

The archaeological context of the teapot lid provides poor constraints on its age. Indeed, since it is not a waster *per se* (although it is undecorated), it could be argued that this teapot lid was not made where it was found. This latter interpretation is supported by the widely held view that A-marked porcelains were made at another site in East London. The teapot lid's association with phosphatic sherds in the same waster pile indicates that it was discarded after the introduction of Bow's 2nd patent (1749). As already noted, the composition of phosphatic sherds found near (but not with) the lid indicate a late 1740s or early 1750s date. Similarly, based on their design characteristics, most other ceramic finds from this dump appear to be from the 1750s.

The success of Bow's 1st patent relied largely on the composition, proportion and grain size of the glass frit used in its manufacture. The composition of the paste

has a direct impact on the amount of melt (i.e., its melt fertility) that can form at the onset of vitrification (i.e., at the eutectic). The patent described a simple formula: one part alkali-lime glass frit to two parts clay. Owen²¹ (2012) used the SiO₂-Al₂O₃-CaO phase diagram²² to evaluate the melting behaviour of this sample at vitrification temperatures.

In principal, the composition of the first melt formed in a ware of this composition²³ should correspond to a thermal minimum (eutectic)²⁴ at 1345°C. It does not do so. Indeed, the composition of the inner, siliceous-aluminous corona around the devitrified glass particles plots near the edge (SiO₂-Al₂O₃ join) of the diagram.²⁵ The melt phase in high-fired ceramics rarely corresponds to compositions predicted by phase diagrams, usually because minute crystals are entrained in the melt, thereby displacing its composition away from eutectics (or cotectics), or because the sample did not equilibrate at high temperature, so melt compositions reflect the nature of neighbouring minerals.

In the present case, an explanation for the displacement of the melt phase (siliceous-aluminous corona) from the 1345°C eutectic is provided by the observation that the CaO apex of the diagram, the 1345°C eutectic, and the composition of the inner corona are collinear. This indicates two key points about the melt in this sample. First, it shows that CaO was removed from the melt phase by the feldspathic corona enclosing it. This must have occurred in the solid state, because the feldspathic corona is porous. Had this outer corona crystallized directly from a melt phase, the pores would have been filled or partly filled by the melt. Second, it shows the composition of the melt initially corresponded to the thermal minimum (1345°C eutectic).

Notwithstanding evidence that the teapot lid initially contained a melt with a eutectic composition, the actual peak firing temperature of the sample would have been considerably less than 1345°C because the lid contains about 8 wt.% total alkalis (Na₂O+K₂O). These compounds serve as a flux, lowering melting temperatures. The extent to which the eutectic is depressed by these fluxes can only be determined by

running firing experiments on A-marked porcelain, or analogues of these wares. Ramsay et al.²⁶ successfully fired an A-marked analogue (a cup) at 1279°C, but its microstructure does not resemble that of actual A-marked porcelain reported here and elsewhere.²⁷

Discussion

One of the main challenges facing the producers of historical porcelains involved creating a translucent ware that resisted body distortion (sagging) in the kiln. These two objectives are at odds with one another, because translucency requires the generation of an abundant melt phase, which weakens the object being fired. However, if the melt phase is highly siliceous and aluminous, as is the case with the teapot lid, it will be very viscous, reducing (but not eliminating) the likelihood of sagging during firing.

There are two strategies porcelain manufacturers can adopt to improve translucency. One involves lowering the vitrification point by increasing the amount of flux in the ceramic paste. This option allows for the generation of a minimum melt at relatively low temperature. Continued firing eventually resorbs a mineral in the ware, allowing the melt to abandon the eutectic, so the temperature of the ware rises above the thermal minimum, and a different composition of melt begins to form. Increasing amounts of melt will form as temperature rises. The only limitation is the ability of the kiln to achieve higher temperatures.

Another strategy involves changing the composition of the paste so that it more closely approaches that of the thermal minimum.²⁸ This allows a higher proportion of minimum melt to form at the onset of vitrification. As it happens, the teapot lid has a moderately high degree of melt fertility (55%). This value could be raised or lowered by increasing or decreasing (respectively) the frit/clay ratio of Heylyn and Frye's paste.

Our assessment of the microstructures and composition of the teapot lid thus allows us to offer some belated advice to Heylyn and Frye. Had they maintained the 1:2 frit to clay ratio stipulated by their first patent but created a more potash-rich glass frit, the vitrification temperature of the paste would have been lowered, increasing the likelihood that at *peak*

kiln temperatures melting would have occurred above the eutectic (i.e., on a cotectic). This would have encouraged the formation of wider melt coronas at the expense of both frit and clay (metakaolin), decreasing porosity and thereby increasing the translucency of the ware.

Alternatively, Heylyn and Frye could have used the same composition of frit, but increased its proportion relative to clay. This would have moved the bulk composition of their 1st patent wares closer to the 1345°C eutectic, increasing the melt fertility of the ware. This would have increased the amount of minimum melt generated during vitrification, thereby decreasing porosity. Either strategy would have created a relatively translucent and therefore aesthetically more pleasing ware that potentially would have been more commercially successful. Moreover, the siliceous-aluminous melt phase²⁹ would have had a very high viscosity³⁰, reducing the likelihood of body distortion at peak kiln temperatures. Thus, had a more potassic frit been used, or a paste with a frit/clay ratio substantially greater than 0.5 (the ratio stipulated in the 1st patent), then a 2nd patent might not have been necessary, and Bow could have continued to produce 1st patent wares into the 1750s and beyond.

It is instructive to speculate on the long term implications of this scenario. Bow was the largest and arguably one of the most successful (surviving three decades) and influential of the London porcelain factories. It was also one of the earliest, if not the first, porcelain manufactory in the UK. It has been demonstrated elsewhere³¹ that technical information about the porcelain industry migrated from London westward and northwestward across the UK, and thence³² to the USA. This highlights the influence that the early London factories (Bow, Limehouse) had on the development of the nascent porcelain industry in Britain and elsewhere. Moreover, it has long been known³³ that during the third quarter of the 18th century, bone-ash (phosphatic) porcelains of the type evidently originating with Bow's 2nd patent came into more common use (with the advent of some of the Liverpool factories) than other types of ware (e.g., so-called frit and soapstone porcelains).

The preferential survival of some of the latter types of ware (e.g., Worcester) has been attributed to their ability to withstand boiling water better than phosphatic pastes, an attribute that can be evaluated using recent experimental data.³⁴ Had Heylyn and Frye's 1st patent paste met with long-term success as the use of a more potassic frit or a paste with a higher frit/clay ratio could have helped ensure, phosphatic pastes (if developed at all) might have been consigned to a side-alley in English porcelain history. Had this been the case, it is interesting to consider whether hybrid hard pastes would have been tried at all and if bone china, now an industry standard, would ever have emerged in Britain.

Conclusions

The microstructure, mineralogy, paste and glaze compositions of the excavated teapot lid are consistent with A-marked porcelain. Moreover, its paste composition closely resembles that stipulated by Heylyn and Frye's 1st patent. Although the currently accepted position is that this porcelain was not manufactured on the Stratford site, the teapot lid was found among

items that were in a context in which very little foreign material has been identified. Thus, although we can offer no explanation on how this artifact came to be on the site, it nevertheless represents the first tangible *archaeological* link between Bow and A-marked porcelain.

Despite their stylistic similarity to A-marked wares, the excavated sherds from the Stratford site described here are phosphatic. Their paste compositions are consistent with a late 1740s/early 1750s age. The composition of their glazes, however, appears to be less useful in dating these samples.

A-marked wares could have been more translucent (and hence aesthetically more pleasing) had Heylyn and Frye made use of a more potassic glass frit, or increased the frit/clay ratio of their paste. Although the specific reasons that their first patent recipe was abandoned are not known, such technical advances could conceivably have forestalled or even circumvented the need for their phosphatic (2nd patent) recipe. This would have had a profound impact on the subsequent history of the British porcelain industry.

ACKNOWLEDGEMENTS

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NOTES

¹ Holden, S & Pearce, J, '14-26 High Street, Stratford, London E15: A post-excavation assessment and updated project design', MoLAS/PCA unpublished report

² Owen, J V, 2012, 'Double corona structures in 18th-century porcelain (1st patent Bow, London, c. 1742-1749): a record of partial melting and subsolidus reactions'. *Canadian Mineralogist* 50, 1255-1264

³ Diopside is a clinopyroxene (CaMgSi₂O₆). Pseudowollastonite is the high-temperature form of wollastonite, a pyroxenoid (CaSiO₃)

⁴ Owen, 2012, op. cit.

⁵ Freestone, I C, 'A-marked porcelain: some recent scientific work', *ECC Transactions*, Vol 16, Pt 1 (1996), pp 76-84

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⁷ Freestone, I C, 1993, 'A technical study of Limehouse ware' in Drakard, D (ed.), *Limehouse Ware Revealed*. (English Ceramic Circle), pp 68-73; Owen, J V, 2000, 'A preliminary assessment of the geochemistry of porcelain sherds from the Limehouse factory site, London'. [Technical Appendix in Tyler, K. and Stephenson, Museum of London monograph 6, *The Limehouse Porcelain Manufactory*, pp 61-63]

- ⁸ Owen, J V and Hillis, M. 2003. 'From London to Liverpool: evidence for a Limehouse - Reid porcelain connection based on the analysis of sherds from the Brownlow Hill factory site'. *Geoarchaeology* 18, 851-882
- ⁹ Owen, J V, 2007, 'A new classification scheme for 18th century American and British soft-paste porcelains', *Ceramics in America 2007*, 121-140
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- ¹¹ Ramsay, W R H and Ramsay, E G, 2007, 'A classification of Bow porcelain from first patent to closure: c. 1743-1774'. *Proceedings of the Royal Society of Victoria* 119, 1-68
- ¹² Freestone (1996) op. cit.
- ¹³ Owen et al. (2011) op. cit.
- ¹⁴ Ramsay and Ramsay (2007) op. cit.
- ¹⁵ Ramsay, W R H, Sutton, K, and Ramsay, E G, 2011. 'Bow porcelain: glaze compositions associated with the phosphatic wares ~1742-1774'. *Proceedings of the Royal Society of Victoria* 123 (2). 161-171
- ¹⁶ Owen, J V, 2013, 'What analytical data can (and cannot) tell us about 18th-century fine ceramics', *ECC Transactions*, Vol 22 (2011), p 215
- ¹⁷ Quick, D, Owen, J V and Hanley, J (submitted). 'Geochemistry of a novel Chelsea (London, mid-18th century) Ca-P-Pb repair glaze: results of analogue firing experiments and implications for authenticating historical porcelains using glaze compositions', *Journal of Archaeological Science*. This paper also shows that the compositions of some glazes can change during kiln firing (i.e. they can behave as an open chemical system)
- ¹⁸ Freestone (1996) op. cit.; Ramsay and Ramsay (2007) op. cit.
- ¹⁹ Ramsay et al. (2004) op. cit.
- ²⁰ Ramsay et al. (2004) op. cit.
- ²¹ Owen (2012) op. cit.
- ²² Osborn, E F and Muan, A, (1960). 'Phase equilibrium diagrams of oxide systems', (Columbus, Ohio, American Ceramic Society)
- ²³ Or any other one plotting in the silica-anorthite-mullite compatibility triangle on this phase diagram
- ²⁴ Eutectics are isobaric invariant points. This means that, at constant pressure, melting at the thermal minimum buffers temperature, which cannot increase in the ware being fired until one subsolidus phase (mineral) is dissolved in the melt. When this happens, the variance of the system increases by one, so the system becomes univariant, so temperature can increase. Melt compositions thus leave the eutectic as temperature rises, tracking a thermal valley (cotectic) on the phase diagram
- ²⁵ Owen (2012), op. cit., Fig. 5
- ²⁶ Ramsay et al (2004), op. cit.
- ²⁷ Freestone (1996), op. cit.
- ²⁸ If the ware has a minimum melt composition (i.e., it plots directly on the eutectic), it will completely melt at eutectic conditions if heated at that temperature for a sufficiently long period of time. The closer the ware plots to the eutectic, the greater its potential melt fertility. This can be measured on the phase diagram using what is referred to as the 'lever rule'
- ²⁹ Microprobe data (Owen [2012, op.cit.]) show that the siliceous-aluminous inner coronas in the teapot lid contain ~74% SiO₂ and 16% Al₂O₃. These values would have been lower before the CaO was extracted by plagioclase growing in the outer, feldspathic corona. Based on the SiO₂-Al₂O₃-CaO phase diagram (Osborn and Muan, 1960 [op. cit.]), the 1345°C eutectic would have a composition of approximately 70% SiO₂, 20% Al₂O₃ and 10% CaO in this alkali-free system
- ³⁰ The log (base 10) of the viscosity (η) of the melt in the teapot lid has been calculated to be 5.3 Pa s at 1200°C (Owen, J V and Yang, X, 'Wherefore and why: geochemical insights on the longevity of William Littler's 'frit' porcelain' (Staffordshire and Scotland, c. 1750-1785). Submitted to *Journal of the American Ceramic Circle*. This compares with melt viscosity values (log₁₀) of 3.9-6.5 Pa s in Nantgarw porcelain, and 3.7 and 5.3 Pa s in William Littler's porcelains (Longton Hall, West Pans, Baddeley-Littler)
- ³¹ Owen and Hillis (2003), op. cit.
- ³² Panes, N, 'Mr Ball the English Potter and the American China Manufactory', *ECC Transactions*, Volume 20, Pt 3 (2009), p 633
- ³³ Honey, W B, (1948), *Old English Porcelain*. (Faber and Faber, 1948), Appendix II
- ³⁴ Coefficients of thermal expansion have recently been reported for individual minerals found in some historical wares (e.g., orthoenstatite found in some 'soapstone' porcelains: cf. Jackson, J M, Palko, J W, Andrault, D, Sinogeikin, S V, Lakshtanov, D L, Wang, J, Bass, J D and Zha, C.-S, 2003, 'Thermal expansion of natural orthoenstatite to 1473 K', *European Journal of Mineralogy* 15, 469-473) and on modern counterparts of early porcelain (e.g., bone china: cf. Mukhopadhyay, T K, Ghosh, S and Ghatak, S, 2011, 'Phase analysis and microstructure evolution of a bone china body modified with scrap addition', *Ceramics International* 37, 1615-1623).