

GEOCHEMICAL EVIDENCE FOR THE MANUFACTURE, LOGISTICS AND SUPPLY-CHAIN MANAGEMENT OF EMPEROR QIN SHIHUANG'S TERRACOTTA ARMY, CHINA*

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Non-invasive materials characterisation of reconstructed statues of Emperor Qin Shihuang's Terracotta Army has revealed distinct micro-geochemical patterning within the clay paste used in their manufacture. The significance of this is explored in terms of the production sequence, logistics and supply-chain management involved in the construction of this enormous funerary assemblage. Of particular interest is a compositional distinction between figures marked with the names 'Gong' (宫) and 'Xianyang' (咸阳). These seem to represent the products of two workshops involved in the supply of ceramic objects for this ambitious, large-scale building project undertaken by the Qin Empire during the third century BCE.

KEYWORDS: CERAMICS, TERRACOTTA ARMY, CHINA, GEOCHEMISTRY, CRAFT MANUFACTURE, PROJECT MANAGEMENT, SUPPLY CHAIN

INTRODUCTION

Emperor Qin Shihuang's Terracotta Army is an ancient ceramic assemblage of immense scale, importance and world renown. It is thought that these approximately 8000 life-sized ceramic soldiers and horses were installed in battle formation in several underground pits outside the tomb of the first emperor of China in order to protect him in the afterlife (Yuan 1990; Ledderose 2001) (Fig. 1, a). This impressive funerary assemblage, as well as the many thousands of other ceramic, metal and stone artefacts unearthed from the first emperor's mausoleum complex, near Xi'an in Shaanxi province, China (Fig. 1, b), have the potential to shed a light on the planning and execution of large-scale building projects by the Qin Empire, including topics such as the division of labour, quality control, standardization and logistics management.

We have recently demonstrated this by studying the mineralogical and microstructural composition of fragments of the terracotta statues and other ceramic objects under the microscope using 30 µm thin sections (Quinn *et al.* 2017). This provided new insights into their manufacturing location and ancient craft technology, as well as the organization of ceramic production at the mausoleum. The ceramic paste used to construct the terracotta statues was found to have been prepared by the addition of local alluvial sand temper to silt-rich wind-blow loess clay. On the other hand, samples of bricks, rammed earth structures and the ceramic core material of ornate bronze waterfowl, also unearthed from the mausoleum, were made according to different paste

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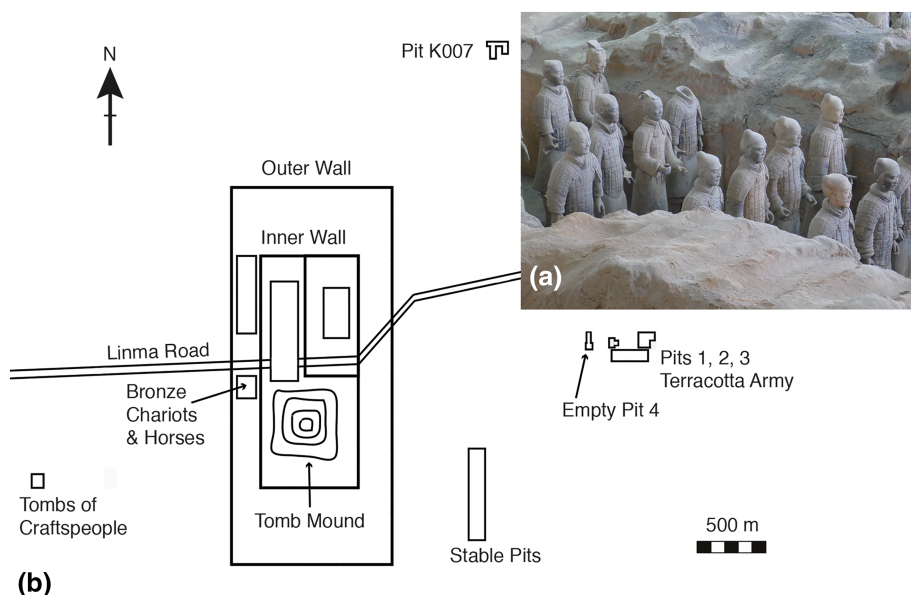


Figure 1 Emperor Qin Shihuang's Mausoleum Site in Shaanxi province, China: (a) ceramic statues of the Terracotta Army arranged in battle formation in Pit 1 of Emperor Qin Shihuang's mausoleum complex near Xi'an, Shaanxi; and (b) plan of the site with the location of Terracotta Army Pits 1–3 and K007. [Colour figure can be viewed at wileyonlinelibrary.com]

recipes, but using the same base clay material. Based on these compositional and technological similarities and differences between the various artefacts, we proposed a model whereby different groups of artisans within a workshop could have been responsible for specific ceramic products, but received their raw materials from a central supply (Quinn *et al.* 2017).

The immense cultural value of the Terracotta Army means that destructive scientific analyses have so far only been conducted on small fragments of the statues (Gao *et al.* 2002; Shan *et al.* 2003; Zhao *et al.* 2003; Quinn *et al.* 2017), most of which lack contextual information. In material studies on ancient ceramics, context is crucial in order to distinguish anthropological signals from natural geological variation in raw materials and differential artefact preservation (Quinn 2013, 71). A novel solution to this problem is the application of non-invasive technologies, such as portable X-ray fluorescence spectroscopy (pXRF) (Tykot *et al.* 2013; Hunt and Speakman 2015; Holmqvist 2016; Tykot 2016; Wilke 2017; Sorresso and Quinn 2020) (Fig. 2). This approach has the potential to characterize chemically complete or partially reconstructed statues of the Terracotta Army *in situ*, and has already been used to investigate the mass production of bronze weapons found at the mausoleum (Martín-Torres *et al.* 2014, 2019).

STUDY MATERIALS AND ANALYTICAL METHODS

Access to the closely packed rows of ceramic sculptures (Fig. 1, a) is today highly restricted. However, a subset of 230 more widely spaced figures is located in a raised conservation area at the back of Pit 1, which is more accessible. These statues, most of which were excavated from Pit 1, include examples of different types, such as armoured warriors, armoured middle-ranking officers, armoured charioteers, horse breeders and terracotta horses (Fig. 2). Several armoured



Figure 2 Different Terracotta Army statue types analysed in this study within the Pit 1 conservation area: (a) armoured warrior with an arm being analysed geochemically via portable X-ray fluorescence spectroscopy (pXRF); (b) armoured middle-ranking officer with his robe under analysis; (c) armoured charioteer; (d) horse breeder; and (e) horse with the portable X-ray fluorescence spectroscopy (pXRF) device analysing a head section. [Colour figure can be viewed at wileyonlinelibrary.com]

warriors feature stamps or inscriptions that are thought to refer to the workshops that produced them, as well serving as a means of quality control and administration (Yuan 1990; Li *et al.* 2016) (Fig. 3). We quantified the geochemical composition of the clay paste of 28 of these restored statues (Table 1), including all marked specimens, by analysing with pXRF their different component parts, including the arms and robe sections of the soldiers and the head and legs of the horses (Fig. 2, a, b, e). Analyses were also made of several ceramic bricks and pipes unearthed from the mausoleum, as well as a profile of natural sediment in within Pit 1, for comparison with the ceramics (Table 1).

In order to address concerns about the data quality of miniaturized pXRF devices (e.g., Speakman and Shackley 2013), we developed a custom calibration for archaeological ceramics that records the abundance of 15 different naturally occurring elements (Wilke *et al.* 2017; Sorresso and Quinn 2020). Irradiation was performed with an Olympus Innox-X Delta Premium handheld device using a Rh source and a 2 mm Al filter. Analysis was undertaken at 40 kV for 120 s live time using 'Beam 2' of the manufacturer's 'Soil' mode. The resulting raw spectra were exported and deconvoluted using Bruker ARTAX software in order to correct for individual interferences, including Rb K β /Y K α , Y K β /Nb K α and Sr K β /Zr K α . Pb absorption and interferences, probably resulting from minor Pb concentrations within residual surface treatments

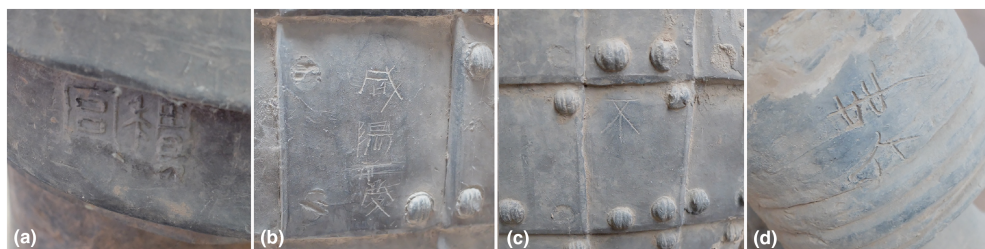


Figure 3 Marking types present on armoured warrior statues within the Pit 1 conservation area that may have had a quality control and/or administrative function, as well as indicating the type of workshop that produced them: (a) stamp on the base of the robe section with the name 'Gong' (宫); (b) inscription on the armour scale of the name 'Xianyang' (咸阳); (c) inscription on the armour scale with the character 'Bu'; and (d) Inscription of the number 46 on arm section. [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1 Details of Terracotta Army statues from the Pit 1 conservation area and other ceramic objects analysed via portable X-ray fluorescence spectroscopy (pXRF) in the present study

Object/sample	Type	Subtype	Excavation location	Marking	Analyses
005448	Soldier	Armoured warrior	Pit 1	Gong	6
005476	Soldier	Armoured warrior	Pit 1	Gong	6
005480	Soldier	Armoured warrior	Pit 1	Gong	6
005647	Soldier	Armoured warrior	Pit 1	Gong	9
005648	Soldier	Armoured warrior	Pit 1	Gong	9
005654	Soldier	Armoured warrior	Pit 1	Gong	6
005666	Soldier	Armoured warrior	Pit 1	Gong	6
005453	Soldier	Armoured warrior	Pit 1	Xianyang	7
005625	Soldier	Armoured warrior	Pit 1	Xianyang	10
005640	Soldier	Armoured warrior	Pit 1	Xianyang	10
005660	Soldier	Armoured warrior	Pit 1	Xianyang	9
002756	Soldier	Armoured warrior	Pit 1	Character Bu	6
005706	Soldier	Armoured warrior	Pit 1	Character Mu	6
005663	Soldier	Armoured warrior	Pit 1	Number 3	6
005456	Soldier	Armoured warrior	Pit 1	Number 5	6
005497	Soldier	Armoured warrior	Pit 1	Number 46	6
005667	Soldier	Armoured warrior	Pit 1	Unknown marking	7
005494	Soldier	Armoured warrior	Pit 1	No marking	6
005499	Soldier	Armoured warrior	Pit 1	No marking	6
005633	Soldier	Armoured middle-ranking officer	Pit 1	No marking	9
005467	Soldier	Armoured middle-ranking officer	Pit 1	No marking	8
006157	Soldier	Horse breeder	Pit K006	No marking	6
006158	Soldier	Horse breeder	Pit K006	No marking	6
005680	Soldier	Armoured charioteer	Pit 1	No marking	6
00844	Horse	Horse	Pit 1	No marking	6
002765	Horse	Horse	Pit 1	No marking	6
002768	Horse	Horse	Pit 1	No marking	6
No Number	Horse	Horse	Pit 1	No marking	6
LXT12B1	Pipe	—	West of mausoleum	No marking	3
LXT12B2	Pipe	—	West of mausoleum	No marking	3
QMC009	Brick	—	Pit 1	No marking	3
QMC011	Brick	—	Pit 1	No marking	3
QMC010	Brick	—	Pit 1	No marking	3
Sediment profile 1	Clay	—	Pit 1	—	3
Sediment profile 2	Clay	—	Pit 1	—	3
Total					213

(see below), were corrected with the algorithms described by Wilke (2016). A Rayleigh scatter distance correction was used to account for the slightly curved shape of some of the samples, for example, the statues' arms and legs. The net counts were converted into concentrations via an in-house calibration developed using a series of homogeneous fired spiked clay samples with four concentrations of the elements Fe, Ga, Nb, Rb, Sr, Ti, Y and Zr (Wilke 2017). These reference samples were developed specifically for pXRF calibration due to the absence of natural geochemical reference materials with just one interfering element of variable concentration and the effected elements having a fixed concentration (Wilke 2017). They have a clay matrix that is

representative for mass absorption of mid-Z elements in a broad range of clay and other aluminosilicates with a total matrix composition of elemental O, Al and Si > 90%. In addition to the nine spiked elements, the calibration also measured Ca, Co, Cu, K, Mn, Pb and Zn, providing data on a total of 15 elements.

Irradiation was carried out on small about 1 cm diameter circular spots in several places on each part of the statue or other artefact in order to account for possible compositional heterogeneity in the clay paste caused by the distribution of large inclusions and other features (Tykot 2016, 46). Each spot was first gently cleaned with ethanol and a cotton swab to remove dust that has accumulated on the surface of the artefact. All measurements were made with the pXRF window in contact or in very close proximity to the object with the device held firm in a tripod (Fig. 2, a, b, e).

The performance of the pXRF device and in-house calibration was assessed by analysing 14 powdered certified reference materials (SARM1, SARM41, SARM42, SARM44, SARM45, SARM48, SARM50, SARM52, SARM69 CGL02, CGL06, CGL07, CGL111 and GBM306–12) (see Appendix S1) held in plastic cuvette cups and covered with a 6 µm prolene film. The accuracy of each recorded element was assessed across the concentration range that typically occurs within prehistoric earthenware ceramics, as determined from three previously published instrumental neutron activation analysis (INAA) data sets (Day *et al.* 2011 on Bronze Age Greece; Quinn *et al.* 2010 on Neolithic Greece; Quinn and Burton 2015 on pre-contact California; Travé Allepuz *et al.* 2014 on medieval Catalonia) (see Appendix S1).

The statues of the Terracotta Army were originally covered with bright polychrome pigment, which was applied to a binding agent composed of organic lacquer, small traces of which remain on some parts of the objects. While these were avoided during our analysis of the clay paste, we first targeted examples of residual decoration in order to identify potential contaminating elements that could have migrated into the ceramic body underneath during the last 2200 years. This revealed the probable use of several colourants, including Han purple ($\text{BaCuSi}_2\text{O}_6$) and blue azurite ($\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$), white cerussite (PbCO_3) and calcite (CaCO_3), all of which have been reported in detailed studies of the polychrome (Hern 2001; Thieme 2001; Xia *et al.* 2004). The analysis of patches of residual lacquer suggests that it contains traces of Cu, most likely coming from the enzyme ‘laccase’, which is known to occur in the sap of the Oriental lacquer tree (Ring 2001). After omitting Ca, Cu and Pb and retaining only those elements that could be recorded with an accuracy of about $\leq 20\%$ relative error (Fe, Ga, K, Nb, Rb, Sr, Ti, Zn and Zr) (see Appendix S1), we investigated possible elemental patterning within different combinations of the multivariate data set of 213 measurements (see Appendix S2) as well as an averaged data set of specific parts of the statues only (see Appendix S3) by reducing it to a smaller number of variables or components via principal component analysis (PCA) and plotting these against each other. We were interested in detecting the geochemical similarities and differences between the different ceramic types, statues and parts thereof that could be related to the use of specific raw material sources and/or paste recipes.

RESULTS AND DISCUSSION

Principal components 1 and 2 from the PCA of the full 213 measurements (see Appendix S2) explain 51% of the total variance in the data set. A scatterplot of the component scores reveals a large, dispersed cloud without obvious compositional groups. By highlighting the analyses of the bricks, pipes and Pit 1 sediment, it can be seen that they plot in the upper edge of the cloud, suggesting that they are chemically distinct from most of the statues of the Terracotta Army (Fig. 4, a). This distinction is due to a lower abundance of the elements Nb and particularly Zr

within the statues, which strongly affect principal component 2. This be explained by the addition of silica-rich sand temper to their ceramic paste (Shan *et al.* 2003; Quinn *et al.* 2017), which would have diluted the natural levels of the mineral zircon (ZrSiO_4) within the silty loess base clay that seems to have been used (Shan *et al.* 2003; Rong and Lan 2005; Quinn *et al.* 2017), relative to the non-tempered bricks and pipes. Temper was most likely added to reduce the stickiness or plasticity of the fine clay and make it more suitable for shaping into the ornate sculptures, as well as to open up the paste of the thick-walled objects, creating pores through which water could migrate during the lengthy drying process (Quinn 2013, 156–8).

It has been proposed that the Terracotta Army figures were manufactured via a modular system in which a limited variety of mass-produced arms, legs, heads and other parts were assembled in

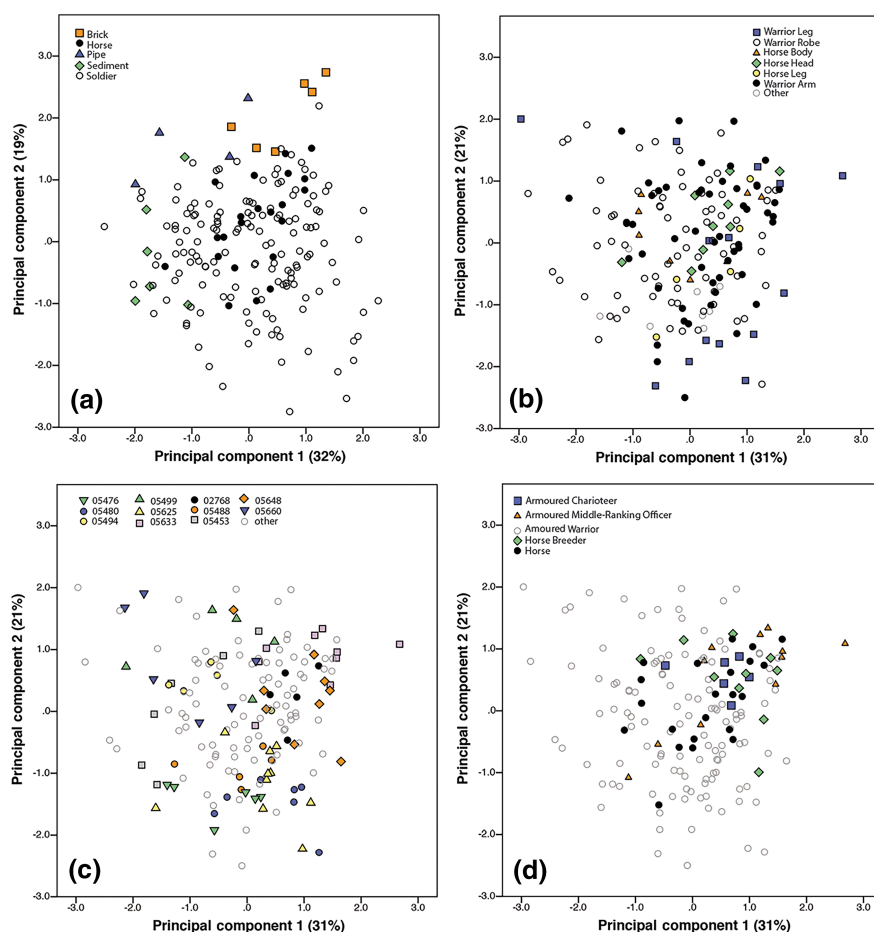


Figure 4 Statistical classification of the multivariate geochemical data on nine major, minor and trace elements (Fe, Ga, K, Nb, Rb, Sr, Ti, Zn and Zr) recorded within the clay paste of Terracotta Army statues, other ceramic objects and Pit 1 sediment, via portable X-ray fluorescence spectroscopy (pXRF): (a) plot of components 1 and 2 from the principal component analysis (PCA) of all analyses ($n=213$), labelled according to sample type; (b) plot of components 1 and 2 from the PCA of statue analyses only ($n=192$), labelled by statue part; (c) the PCA plot of statue analyses only, with the analyses of specific figures indicated; and (d) the PCA plot of statue analyses only, with the statue type indicated. [Colour figure can be viewed at wileyonlinelibrary.com]

different combinations to give the impression of an army of unique individual soldiers (Ledderose 2000). Under this interpretation we might expect to find geochemical similarities between the same parts of different figures. However, by removing the bricks, pipes and sediment measurements, rerunning the PCA and highlighting the analyses of specific statue components in a scatterplot of components 1 and 2, which explain 52% of the total variance in this reduced data set of 192 measurements, it can be seen that they each display significant compositional variability (Fig. 4, b). Furthermore, analyses of the different component parts of specific individual statues each plot together in a somewhat restricted part of the dispersed scatter (Fig. 4, c), indicating their relative geochemical homogeneity. These two patterns do not appear to be in keeping with the idea of a modular production system in which the Terracotta Army figures were assembled from prefabricated components that were perhaps made in several workshops with different raw materials and/or paste preparation techniques. Instead, the findings are more in line with an alternative hypothesis that each complete terracotta figure was individually created by a single workshop or group of artisans (Martínón-Torres *et al.* 2014; Li *et al.* 2016) using the same recipe and perhaps a single batch of clay.

By highlighting the measurements of the armoured middle-ranking officer, armoured chariot-er, horse breeder and horse statues in the PCA scatterplot (Fig. 4, d), it can be seen that they have a less diverse chemical composition than the armoured warriors within this second data set. This could suggest that these less common statue types had a more standardized paste recipe or that they were made from a common clay source. It might even indicate that they were made by a single workshop over a shorter space of time. The wider spread of the analyses of the dominant armoured warriors is due to an overlap between analyses of the those statues stamped with the name ‘Gong’ (宮), meaning the residence of ancient emperors or immortals (Fig. 3, a), and those inscribed with ‘Xianyang’ (陽), the capital city of the Qin Empire (Fig. 3, b), which are the two most common types of markings found on the Terracotta Army (Fig. 5, a) (Yuan 1990; Li *et al.* 2016). In order to focus on these, we retained only the analyses of the arms and robe sections of the soldiers, and the head and upper legs of the horses, upon which we recorded at least three different spots for each statue. By averaging the replicate measurements for each statue part (see Appendix S2), we can reduce noise in the data set caused by the narrow beam of the pXRF and the compositional heterogeneity inherent in coarse ceramic pastes (Tykot 2016). The PCA of the resulting averaged data set ($n=56$) explains 56% of the total variance and reveals a clear separation of the statues marked with Gong and Xianyang (Fig. 5, b). This due to them having different concentrations of the elements Rb and Sr, which strongly affect principal components 1 and 2, respectively. The separation of the Gong and Xianyang statues can also be clearly seen in a scatterplot of these two elements (Fig. 5, c).

The current interpretation of the Gong stamps is that they refer to a large group of ‘royal’ or ‘imperial’ workshops, located somewhere close to the mausoleum that also specialized in the production of ceramic construction materials, including bricks and roof tiles (Yuan 2014; Li *et al.* 2016), some of which bear the same marking type found on the statues. The Xianyang inscriptions, on the other hand, are thought to signify the products of a second group of artisans coming from a distinct locus somewhere in the capital city of Xianyang, 50km away, who were also working close to the mausoleum (Li *et al.* 2016). The clear distinction in our statistical analysis of the averaged geochemical data of the arms and robe sections of the armoured warriors between statues with these two marking types (Fig. 5, b, c) seems to support the idea that they represent the products of different types of workshops.

While we cannot rule out that the unique geochemical composition of the Gong and Xianyang statues could be due to different decorative treatments. This seems unlikely as there is currently

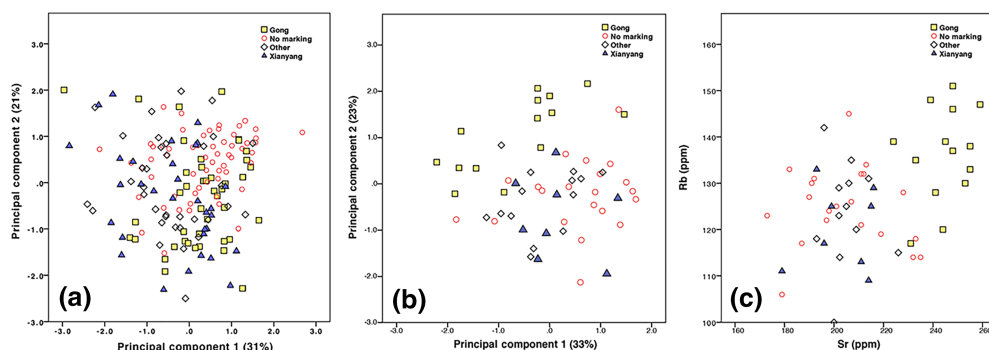


Figure 5 Statistical classification of multivariate geochemical data on nine major, minor and trace elements (Fe, Ga, K, Nb, Rb, Sr, Ti, Zn and Zr) recorded within the clay paste of Terracotta Army statues via portable X-ray fluorescence spectroscopy (pXRF): (a) plot of components 1 and 2 from the principal component analysis (PCA) of statue analyses only ($n = 192$), labelled by marking type; (b) plot of components 1 and 2 from the PCA of the averaged geochemical composition of arms and robes of warrior statues and legs and head of horses ($n = 56$), labelled by marking type; and (c) plot of the concentration of the averaged values of Sr and Rb in arms and robes of warrior statues and head and legs of horses ($n = 56$), labelled by inscription type. [Colour figure can be viewed at wileyonlinelibrary.com]

no evidence of such practices in terms of the remnant colour or finish of the excavated marked statues. Additionally, the elements Sr and Rb have not been reported in detailed studies on the pigments used in the polychrome decoration or the lacquer layer (Hern 2001; Thieme 2001; Xia *et al.* 2004). Ancient ceramics can be altered and contaminated mineralogically and chemically over time (Freestone 2001; Quinn 2013, 204–10), a process that could perhaps explain the measured chemical differences. However, the analysed marked statues were all excavated from Pit 1 of the mausoleum and may not therefore have been subjected to different environmental conditions during burial. Furthermore, the X-rays generated by Sr and Rb during the pXRF analysis of silica-rich material are known to originate from greater depths than those of lighter elements (Adlington and Freestone 2017), suggesting that the signals detected in the present study reflect the composition of the ceramic paste rather than post-depositional contamination of the surface of the statues or residual decoration. The most likely explanations for the compositional distinction in our data set between the statues marked with the names Gong and Xianyang, respectively, are therefore the use of different raw material sources and/or paste preparation recipes by the two workshops.

Wind-blown loess, which covers much of central and northern Shaanxi province and is likely to be the source of the base clay used for the manufacture of the ceramics at the mausoleum (Shan *et al.* 2003; Rong and Lan 2005; Quinn *et al.* 2017), can be compositionally homogeneous over large areas (Sun 2002). However, minor variation in the mineralogy of the clay- and silt-rich source material over time or from place to place, due to the mixture of wind-blown sediment and alluvial material, can result in differences in trace elements that make up $< 0.1\%$ of the total composition of naturally occurring clay deposits (e.g., Zhao *et al.* 2003, 94–5, table 3). In geochemical studies of the production location or provenance of ancient ceramics, trace elements are of prime importance for distinguishing between artefacts made from different clay sources (Glascock *et al.* 2004; Minc and Sterba 2017). Both Sr and Rb, which differ between the Gong and Xianyang statues in our data set, have proved to be discriminatory in many published studies worldwide (Kuleff and Djingova 1996), including several conducted with pXRF (Morgenstein and Redmount 2005;

Tykot *et al.* 2013; Wilke *et al.* 2017; Braekmans *et al.* 2019), as well as in the study of other inorganic artefacts such as glass (Adlington and Freestone 2017). This is due to their presence in certain minerals (e.g., K-feldspar and plagioclase) in the original source rocks of clay deposits (Degryse and Braekmans 2014). With this in mind, it is possible to envisage the suspected Gong and Xianyang workshops obtaining clay from separate sources, each with its own slightly different geochemical pattern. While the location of these deposits cannot be determined without extensive fieldwork and analysis, they need not be particularly distant from each other. It is often assumed that the delicate 150–200kg statues were made close to the mausoleum due to the effort that would have been involved in moving them (Li *et al.* 2016). Fragments of terracotta warrior statues and possible kilns were reported about 200m from Pit 1 during the construction of the site museum in the 1970s (Yuan 1990; Ledderose 2001), though these were not investigated in detail and further direct evidence of production has not been forthcoming.

Potters rarely use clay direct from the ground, but instead manipulate their paste in several possible ways depending on its characteristics and the types of objects they wish to create. This can significantly alter the textural, mineralogical and chemical composition of the original raw material (Sterba *et al.* 2009; Fowler *et al.* 2019). Three common methods of paste preparation that are used by traditional artisans in the present day and which were also practiced in the past are refining, clay mixing and tempering (Quinn 2013, 154–71). Microscopic evidence in thin section suggests that tempering (Shan *et al.* 2003; Quinn *et al.* 2017) and perhaps clay mixing (Quinn *et al.* 2017) were employed in the production of ceramics at the mausoleum. It is therefore possible that the Gong and Xianyang artisans treated their raw materials differently, perhaps even using a single clay source, but adding temper of different types and/or quantities. This would have resulted in their respective ceramic products having distinct geochemical patterns, as detected in our data set. Distinguishing between this technological explanation and the possible use of separate clay sources by the two groups of workshops is unfortunately not possible based on bulk geochemical data alone. It would require the invasive thin sectioning of ceramic fragments from figures bearing the two marking types, which is not currently possible due to their rarity and cultural value.

Turning to the geochemical analyses of the statues bearing other rarer marking types such as single characters (Fig. 3, c) and numbers (Fig. 3, d), as well as those lacking visible stamps or inscriptions, it can be seen that they are geochemically related to those marked with the name Xianyang, but not with the measurements of the Gong statues (Fig. 5, b, c). This may be indicative of the source of these figures, which in our data set consist of the armoured middle-ranking officers, armoured charioteers, horse breeders, horses as well as several armoured warriors, as well as the specific roles of the different workshops. A detailed reassessment of the marking practices of 1087 statues within the easternmost five trenches of Pit 1 (Li *et al.* 2016) suggests that single characters could refer to the names of specific artisans within each of the two types of workshop and numbers may have served a quality control or administrative function. As many as 60% of these statues do not feature any stamps or inscriptions, indicating that marking was not a frequent practice. It is therefore conceivable that the unmarked and ‘other’ marked statues in our data set were manufactured by the Xianyang artisans, but not inscribed with the workshop’s name. This could suggest that the Xianyang workshops produced a range of statue types for the mausoleum, in addition to the more common armoured warriors. The Gong workshops clearly manufactured armoured warriors, but may not have produced armoured middle-ranking officers, armoured charioteers, horse breeders or horses. Gong stamps have also been found on roof tiles (Yuan 2014) as well as ‘robed warriors’ (Li *et al.* 2016) not analysed in our data set.

The data recorded on complete Terracotta Army statues via the pXRF in the present study provide insights into the as-yet-unexplained compositional patterning seen in earlier destructive

geochemical research on larger numbers of poorly contextualized fragments using INAA (Gao *et al.* 2002). Unfortunately, no elemental values were made available in this previous study, so direct comparison with our findings is not possible. However, it perhaps seems plausible that the geochemical differences that Gao *et al.* (2002, 68, fig. 3) recorded both between and within ceramic fragments excavated from Pits 1–3 is due to the presence of statues manufactured by different groups of artisans, such as the Gong and Xianyang workshops discussed above.

It is common in the execution of large-scale, long-term construction projects in the present day for materials and components (e.g., cement, bricks, tiles) to be procured from more than one source, and for the supply chain to change and adapt over time in response to both unexpected difficulties and strategic decisions. The construction of the Terracotta Army, as well as the wider mausoleum complex that it forms part of, seems to have also been a ‘multi-vendor’ project, with several different suppliers contributing similar objects to the scheme. The Gong or Palace workshops whose artisans possessed their own stamps and are thought to have been responsible for the most consistent quality statues (Li *et al.* 2016) were ‘centralized specialists’ (Sinopoli 1988) who were part of the official ‘internal supply chain’ of the project (Pryke 2009). This was supplemented by the products of the Xianyang artisans, who inscribed their work by hand, as well potentially statues manufactured from other as-yet-unknown workshops. Such a diverse multi-source supply-chain management structure may have been needed to meet the economy of scale required for the realization of the ambitious and previously unprecedented project in a relatively short space of time. It would have also helped mitigate possible operational risks presented by stoppages or technical difficulties at one or more of the workshops.

Logistics, which can be defined in the context of construction as the process of mobilizing the various resources required for large-scale building projects (Guffond and Leconte 2005), is a practice that originated from ancient warfare (Sullivan *et al.* 2010), where the organization of supplies, stores and quarters were essential in order to support troop movements. It is therefore no surprise that the powerful Qin army, which unified the Warring States to form the first Chinese empire and maintained tight control on many aspects of life, would have applied military logistics to the planning and execution of the mausoleum of its leader, Emperor Qin Shihuang.

CONCLUSIONS

Our research clearly demonstrates the significant potential of non-invasive technologies for the materials’ characterization of the ceramics of the Terracotta Army. pXRF was used to detect geochemical differences between the clay paste of reconstructed examples of the 8000 or so life-sized statues and other types of clay-based objects and structures at the site. This can be explained by microscopic evidence seen in thin section for the application of specific raw material preparation techniques to the paste of the terracotta figures. A clear compositional signal has also emerged between armoured warrior statues marked with what has long been suspected to be the names of two different types of workshops responsible for their manufacture. This appears to be related to the use of separate clay sources and/or the differential manipulation of the paste used to manufacture the statues of each producer. It is a significant step forward in our understanding of the construction of the Terracotta Army in that it represents the first scientific evidence to support this theory. This in turn permits the discussion of important topics such as the logistics and supply-chain management involved in the project. These would surely have been carefully thought out given the high degree of organization and efficiency seen in many other aspects of Qin society, and were a crucial element in the construction of this enormous funerary monument in time for the First Emperor’s death in 210 BCE. The assignment of the unmarked statues of less

common types, such as horses and officers, to a possible source based on their chemical correspondence to the stamped and inscribed figures has enabled us to consider the specific roles of the different workshops, which seem to have been distinct, yet overlapping. Finally, comparisons between the geochemical composition of various parts of the same reconstructed statues have shed a fresh light on their production sequence, notably the long-standing question of whether they were made by assembling various mass-produced modules or individually crafted by a single group of artisans. The latter seems more likely, given the close chemical composition of different parts of individual statues. Our research suggests that it may be possible to assign further unmarked Terracotta Army statues and even perhaps small broken fragments, of which there are many thousands, to one of the two workshop types. This can be performed without the need for physical sampling of these culturally important, highly protected relics, and will form a major goal of future going research.

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PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/ARCM.12613>. [Correction added on 10 December 2020, after first online publication: Peer review history statement has been added.]

REFERENCES

- Adlington, L. W., and Freestone, I. C., 2017, Using handheld pXRF to study medieval stained glass: A methodology using trace elements, *Materials Research Society Advances*, **33/34**, 1785–800.
- Braekmans, D., Boschloos, V., Hameeuw, H., and Van der Pere, A., 2019, Tracing the provenance of unfired ancient Egyptian clay figurines from Saqqara through non-destructive X-ray fluorescence spectrometry, *Microchemical Journal*, **145**, 1207–17.
- Day, P. M., Quinn, P. S., Kilikoglou, V., and Rutter, J. A., 2011, World of goods: Transport jars and commodity exchange at the late bronze Age Harbor of Kommos, Crete, *Hesperia*, **80**, 511–58.
- Degryse, P., and Braekmans, D., 2014, Elemental and isotopic analysis of ancient ceramics and glasses, in *Treatise on geochemistry. Second edition Vol 14, archaeology and anthropology* (ed. T. E. Cerling), 191–207, Elsevier-Pergamon, Oxford.
- Fowler, K. D., Middleton, E., and Fayek, M., 2019, The human element: Discerning the effects of potter's behavior on the chemical composition of ceramics, *Archaeological and Anthropological Sciences*, **11**, 171–98.
- Freestone, I. C., 2001, Post-depositional changes in archaeological ceramics and glasses, in *Handbook of archaeological sciences* (eds. D. R. Brothwell and A. M. Pollard), 615–25, Wiley, Chichester.
- Gao, Z. Y., Zhao, W. J., Li, G. X., Xie, J. Z., Han, G. H., Feng, S. L., Fan, D. Y., Zhang, Y., Chai, Z. F., Li, R. W., Zhang, Z. L., & Zhu, J. X. (2002) Neutron Activation Analysis on the Raw Material of Terracotta Warriors and Horses of Qin Shihuang Mausoleum. *Science in China*, **32**900–6.

- Glascocock, M. D., Neff, H., and Vaughn, K. J., 2004, Instrumental neutron activation analysis and multivariate statistics for pottery provenance, *Hyperfine Interactions*, **154**, 95–105.
- Guffond, J., and Leconte, G., 2005, Developing construction logistics management: The French experience, *Construction Management and Economics*, **18**, 679–87.
- Hern, C., 2001, Analysis of the painting materials, in *The terracotta Army of the first Chinese emperor Qin Shihuang* (eds. C. Blänsdorf, E. Emerging, and M. Petzet), 371–6, ICOMOS, Paris.
- Holmqvist, E., 2016, Handheld portable energy-dispersive X-ray fluorescence spectrometry (pXRF), in *The Oxford handbook of archaeological ceramic analysis* (ed. A. M. W. Hunt), 363–81, University Press, Oxford.
- Hunt, A. M. W., and Speakman, R. J., 2015, Portable XRF analysis of archaeological sediments and ceramics, *Journal of Archaeological Science*, **53**, 626–38.
- Kuleff, T., and Djingova, R., 1996, Provenance study of pottery: Choice of elements to be determined, *Revue d'Archéométrie*, **20**, 57–67.
- Ledderose, L., 2000, A magic Army for the emperor, in *Ten thousand Yhings. Module and mass production in Chinese art* (ed. L. Ledderose), 51–73, Princeton University Press, Princeton.
- Ledderose, L., 2001, The magic Army of the first emperor, in *The Terracota Army of the first Chinese emperor Qin Shihuang* (eds. C. Blänsdorf, E. Emerging, and M. Petzet), 273–307, ICOMOS, Paris.
- Li, X., Bevan, A., Martínón-Torres, M., Xia, Y., and Zhao, K., 2016, Marking practices and the making of the Qin terracotta Army, *Journal of Anthropological Archaeology*, **42**, 169–83.
- Martínón-Torres, M., Li, X., Xia, Y., Bevan, A., Ma, S., Huang, J., Wang, L., Lan, D., Liu, J., Zhao, Z., Zhao, K., and Rehren, T., 2019, Surface chromium on terracotta Army bronze weapons is neither an ancient anti-rust treatment nor the reason for their good preservation, *Nature Scientific Reports*, **5289**, 1–1.
- Martínón-Torres, M., Li, X., Bevan, A., Xia, Y., Zhao, K., and Rehren, T., 2014, Forty thousand arms for a single emperor: From chemical data to labor organization in the production of bronze arrows for the terracotta Army, *Journal of Archaeological Method and Theory*, **21**, 534–62.
- Minc, L. D., and Sterba, J. E., 2017, Instrumental neutron activation analysis (INAA) in the study of archaeological ceramics, in *The Oxford handbook of archaeological ceramic analysis* (ed. A. M. W. Hunt), 424–46, Oxford University Press.
- Morgenstein, M., and Redmount, C. A., 2005, Using portable energy dispersive X-ray fluorescence (EDXRF) analysis for on-site study of ceramic sherds at El Hibeh, Egypt, *Journal of Archaeological Science*, **32**, 1613–23.
- Pryke, S., 2009, Introduction, in *Construction supply chain management: Concepts and case studies* (ed. S. Pryke), 1–9, Wiley-Blackwell, Oxford.
- Quinn, P. S., 2013, *Ceramic petrography: The interpretation of Archaeological Pottery & Related Artefacts in thin section*, Archaeopress, Oxford.
- Quinn, P. S., and Burton, M., 2015, Ceramic distribution, migration and cultural interaction among late prehistoric (ca. 1300–200 B.P.) hunter–gatherers in the San Diego region, Southern California, *Journal of Archaeological Science Reports*, **5**, 285–95.
- Quinn, P. S., Zhang, S., Yin, X., and Li, X., 2017, Building the terracotta Army: Ceramic craft technology and organisation of production at Qin Shihuang's mausoleum complex, China, *Antiquity*, **91**, 966–79.
- Quinn, P. S., Day, P. M., and Kilikoglou, V., 2010, Keeping an eye on your pots: The provenance of Neolithic ceramics from cyclops cave on the island of Youra, Greece, *Journal of Archaeological Science*, **37**, 1042–52.
- Ring, U. 2001. Chemical analysis pf east Asian lacquer (qi-lacquer). In *The Terracota Army of the first Chinese emperor Qin Shihuang* (eds. C. Blänsdorf, E. Emerging, and M. Petzet), 463–93.
- Rong, B., and Lan, D., 2005, Polarized light microscopy on the fragments of Qin terracotta, *Sciences of Conservation and Archaeology*, **17**, 35–9.
- Shan, J., Zhou, J. Z., Wang, C. S., Qiu, P., Zhang, Z. L., Zhu, J. X., and Zhang, Y. L., 2003, Preliminary study of provenance and firing style of terracotta from Qinshihuang mausoleum, *Nuclear Techniques*, **26**, 299–305. [In Chinese].
- Sinopoli, C., 1988, The organisation of craft production at Vijayanagara, South India, *American Anthropologist*, **90**, 580–97.
- Sorresso, D. C., and Quinn, P. S., 2020, Re-examining Shell-tempered Chickasaw Pottery in Post-contact Mississippi, USA, *Journal of Archaeological Science Reports*, **32**. <https://doi.org/10.1016/j.jasrep.2020.102415>
- Sullivan, G., Barthorpe, S., and Robbins, S., 2010, *Managing construction logistics*, Wiley-Blackwell, London.
- Speakman, R. J., and Shackley, M. S., 2013, Silo science and portable XRF in archaeology: A response to Frahm, *Journal of Archaeological Science*, **40**, 1435–43.
- Sterba, J. H., Mommsen, H., Steinhauser, G., and Bichler, M., 2009, The influence of different tempers on the composition of pottery, *Journal of Archaeological Science*, **36**, 1582–9.

- Sun, J., 2002, Provenance of loess material and formation of loess deposits on the Chinese loess plateau, *Earth and Planetary Science Letters*, **203**, 845–59.
- Thieme, C., 2001, Paint layers and pigments on the terracotta Army: A comparison with other cultures of antiquity, in *The Polychromy of antique sculptures and the terracotta Army of the first Chinese emperor: Studies on materials, painting techniques, and conservation. International conference in Xi'an, Shaanxi museum, march 22–28, 1999* (eds. W. Yongqi, Z. Tingbao, M. Petzet, E. Emerging, and C. Blansdorf), 52–8, Bayerisches Landesamt für Denkmalpflege, München.
- Travé Allepuz, E., Quinn, P. S., López Pérez, M. D., and Padilla Lapuente, J. I., 2014, One hundred sherds of Grey: Compositional and technological characterization of medieval Greyware pottery production at Cabrera d'noia, Catalonia, Spain, *Archaeological and Anthropological Sciences*, **6**, 397–410.
- Tykot, R. H., 2016, Using nondestructive portable X-ray fluorescence spectrometers on stone, ceramics, metals, and other materials in museums: Advantages and limitations, *Applied Spectroscopy*, **70**, 42–56.
- Tykot, R. H., White, N. M., Du Vernau, J. P., Freeman, J. S., Hays, C. T., Koppe, M., Hunt, C. N., Weinstein, R. A., and Woodward, D. S., 2013, Advantages and disadvantages of pXRF for archaeological ceramic analysis: Prehistoric pottery distribution and trade in NW Florida, in *Archaeological chemistry VIII* (eds. R. A. Armitage and J. H. Burton), 233–44, American Chemical Society, Washington D.C..
- Wilke, D., 2017, Some updated quality concerns on non-destructive geo-chemical analysis with XRF spectrometry, *Advances in Applied Science Research*, **8**, 90–4.
- Wilke, D., 2016, Pb correction algorithms for non-destructive provenancing of lead and tin glazed slip wares, *Universal Journal of Material Science*, **4**, 125–32.
- Wilke, D., Rauch, D., and Rauch, P., 2017, Is non-destructive provenancing of pottery possible with just a few discriminative trace elements? *Science & Technology of Archaeological Research*, **2**, 141–58.
- Xia, Y., Zhou, T., and Zhang, Z., 2004, Application of powdered samples polarized light microscopy in identification of artists' pigments, *Sciences of Conservation and Archaeology*, **16**, 32–5. [In Chinese].
- Yuan, Z., 2014, *Archaeological discoveries and research on the Qin terracotta warriors*, Wenwu Press, Beijing.
- Yuan, Z., 1990, *Research on the terracotta warriors and horses from the mausoleum of emperor Qin Shihuang*, Cultural Relics Press, Beijing [In Chinese].
- Zhao, W., Zuo, A., Li, R., Gao, Z., Li, G., Xie, J., Han, G., Zhang, Z., Zhu, J., Feng, S., and Chai, Z., 2003, An analysis of the scattering of Dactylogram elements on Terra-cotta warriors and horses from pit I at the mausoleum of the first Qin emperor, *Huaxia Archaeology*, **2003**, 92–6. [In Chinese].

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.