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Mapping an archaeological site: Interpreting portable X-ray fluorescence (pXRF) soil analysis at Boroughgate, Skelton, UK

Rhys Williams[a,b,*], David Errickson[c], Gillian Taylor[a,b]

[a]School of Health and Life Sciences, Teesside University, Middlesbrough, Tees Valley, TS1 3BX, United Kingdom

[b]National Horizons Centre, 38 John Dixon Lane, Darlington, DL1 1HG, United Kingdom

[c]Cranfield Forensic Institute, Cranfield University, Defence Academy of the United Kingdom, Shrivenham, SN6 8LA United Kingdom

*Corresponding author: rhys.williams@tees.ac.uk

Abstract

Integrating chemical soil analysis with visual inspection of an archaeological excavation may enhance our knowledge of anthropogenic activities from past populations. Elemental distribution of excavated soil from a medieval longhouse at Boroughgate, Skelton, UK was investigated. Soil was extracted from the surface of a longhouse and nearby ditch, analysed using portable X-Ray fluorescence (pXRF), and data were processed into elemental heat maps. The distribution and archaeological associations of magnesium, aluminium, phosphorus, sulphur, potassium, calcium, manganese, iron and zinc were assessed. Elemental concentrations were combined to produce a simplified summary that aided the interpretation of the site, including the delimitation of internal and external zones, clean and refuse zones, and potential animal occupation or waste areas. The application of pXRF was successful at visualising elemental distribution of an excavation to explore the anthropogenic associations through interpretation heat maps.

Key Words: Activity zones; Elemental analysis; Mapping; Portable X-ray fluorescence; Soil analysis

Highlights

- Portable X-ray fluorescence provides rapid survey and mapping of soil
- Elemental soil analysis identified activity areas of an archaeological excavation
- pXRF soil analysis can support and enhance archaeological interpretations

1. Introduction

Boroughgate is a 12th Century medieval borough in the West of Skelton, North Yorkshire, UK, near the All Saints' Old Church and Skelton Castle. Boroughgate was an attempt at establishing a town near Skelton Castle to improve trade and income, including a baker, butcher, fuller, goldbeater, innkeeper, merchant, potter, smith, tanner, and a weaver (Harrison, 1971). The town was deserted around 1400 AD, leaving evidence of medieval ploughing and the boundaries of several properties. The 2018 excavations of the earthworks that remain at Boroughgate, Skelton aimed to establish the location of properties and their uses, identify differences between northern and southern areas of the site, and to corroborate with the craft activities discussed in the medieval documentation (Adams and Daniels, 2019; Errickson *et al.*, 2017). Research into the use of space, social organisation, and activities from archaeological excavations are key to understanding past societal practices and structures of historic communities. This research investigates using portable X-ray fluoresence (pXRF) to map the elemental concentration and distribution within soil at Boroughgate to assist interpretations of the site and demonstrate potential for integration with standard archaeological fieldwork practices (Frahm and Doonan, 2013; Speakman and Shackley, 2013). pXRF offers a rapid, economical, non-detructive and accessible survey tool for determining the total elemental concentration of archaeological sites of all sizes without requiring extensive post-hoc testing with laboratory techniques.

Elemental soil analysis has the potential to support investigations into suspected anthropogenic activities (Pastor *et al.*, 2016; Vranová *et al.*, 2015; Nielsen and Kristiansen, 2014; see Table 1). The exact use of elements as indicative markers of activity and occupation is complex and challenging. Horák *et al.* (2018) grouped elements in relatively high concentrations with having direct connections to the medieval village Lovětín (copper, zinc and thorium) and elements with lower concentrations being within the village vicinity (titanium, chromium, manganese, nickel and zirconium). Middleton (2004) observed higher concentrations of all elements in internal areas, the food zones showed enriched phosphorus, calcium and organic matter whereas burning zones showed enriched phosphorus, potassium, calcium and iron. Fleisher and Sulas (2015) observed better correlations of sodium, magnesium, calcium, and strontium with public spaces, whilst phosphorus, potassium, manganese, iron and daub (a form of clay plastering) correlated more with private spaces. However, sediment from manuring contains high concentrations of potassium and calcium (Nielsen and Kristiansen, 2014), contradicting aspects of the private and public spaces but may be useful for identifying historic farming communities. To overcome this, Fleisher and Sulas (2015) concluded their site as a 'busy, open space with a range of activities for the whole public' rather than specifying activities.

The anthropogenic soil must be altered in comparison to the naturogenic soil, identifiable when compared to the background, parent material or comparative areas, and elemental traces must persist throughout the burial period (Aston *et al.*, 1998; Entwistle *et al.*, 1998). Essentially, an element must have a distinct elemental fingerprint to be useful for archaeological elemental analysis (Wilson *et al.*, 2008), preventing major elements such as silicon and aluminium being of much use due to their lack of distinction although, these are still routinely analysed and reported in multi-elemental geochemical interpretation studies (Bojórquez-Quintal *et al.*, 2017; Cook *et al.*, 2006). This research therefore aimed to explore potential archaeological interpretations of space and societal practice by using multi-elemental pXRF analysis of the soil at Boroughgate. This also aimed to incorporate data mapping for simplified presentation of complex geochemical data and interactions for the public.

Table 1: Summary of generalised potential archaeological interpretations of multi-elemental analysis. Certain elements may be site-specific and have different usefulness or adjusted interpretations due to the impact of natural soil variation and geochemical factors between sites.

Element	Application	Interpretation
Mg	Waste area	Can identify ash-tipping and heavy refuse disposal, but often undetected in soil and requires highly sensitive equipment.
Al	Delimit zones Preservation	Soil dominance reduces value. Indirectly identifies areas of interest or preservation when compared with other elements (low Al, high P). Dominance in soil limit the interpretive value of Al.
Si	None	Wide variation and soil dominance limit interpretive value
P	Burials Delimit zones Food area Occupation Type Preservation	Relatively lower P = naturogenic area, external boundary Relatively higher P = better preservation, activity areas, food and waste, internal boundary Very high P = potential burial area
S	Preservation	Low S = potentially better preservation High S = potentially poor preservation and corrosion

		S is oxidation dependant and does not implicate activity areas.
Cl	Conservation	High concentrations help inform conservation process. Little assistance in other applications. Difficult to detect reliably.
K	Delimit zones Preservation Waste area	Helps delimit zones when combined with P, but less reliability when used alone. Can identify clean, internal zones and areas of manuring.
Ca	Burials Delimit zones Food area Waste area	Relatively lower Ca = clean area Relatively higher Ca = refuse, food preparation areas, some bone Very high Ca = potential area of bones and burials
Mn	Activity	Reported associations with activity and painted buildings, but not observed at Boroughgate
Fe	Delimit zones Food area Preservation Waste area	Can indicate preservation, though Fe can leach from many objects. Identifies burning and butchery zones. Helps delimit zones when combined with P
Zn	Activity Delimit zones	Burning and organic refuse Can help delimit zones, but low reliability

2. Method

Earthwork and geophysical surveys of Boroughgate were completed previously (Errickson *et al.*, 2017). Maps of the Boroughgate area and artefact findings are provided in the supplementary information. Boroughgate has freely-draining slightly acid loamy soils within an area of slowly permeably seasonally wet acid loamy and clayey soils, a landscape that strongly slopes toward the old church and Skelton castle, and steep banks on the East and West sides of Boroughgate. The entire length of Boroughgate is approximately 1 Km North-South and 0.2 Km East-West. The trenches excavated at Boroughgate are approximately 1-3 m North-South and 5 m East-West.

Soil from two trenches were sampled for pXRF analysis. Trench A (Figure 1) was a medieval longhouse and Trench D (Figure 2) was a suspected refuse site and wall. The soils of the site are described in detail by (Adams and Daniels, 2019). The background soil of Boroughgate was also sampled several meters away from Trench A. Briefly, the natural deposit of Trench A was orange brown silt-clay, overlayed by a mottled brown/orange silt clay containing medieval finds; this layer was sampled for pXRF analysis. Trench D contained three parallel ditches in sequence that were contemporary with each other, with no stratigraphic relationship and probable erosion on the East side of the ditch (Adams and Daniels, 2019). These are marked Soil Context 1-3 in Figure 2**.** Soil Context 1 had red brown clay, Soil Context 2 had dark red/brown clay with some silt, and Soil Context 3 had dark red/brown clay. Trench D was sealed by a layer of clayey soil.

Trench A was coordinated and sampled in the centre of every 1 m grid (Figure 1), resulting in 33 samples for Trench A. Trench D was also coordinated, with samples extracted from nine files spaced 1 m apart, and three ranks of samples extracted 40 cm apart (Figure 2), resulting in 27 samples for Trench D. Artefact findings discovered in Trench A include: fragmented and remodelled wall foundations in the east side (A1-5, B1-4, C3), stone pads for building foundations in the centre (E4, F4, G4), a gully intersecting the south border (D5-G5), a second gully with 57 pieces of medieval pottery, daub fragments and clinker intersecting the centre and West sides (H2-3), 21 pieces of charred material typical of medieval Britain contexts toward the North border (D2, E3), and 142 fragments of pottery and one broken stone bowl in the West posthole (I3).

Artefacts from Trench D include: a ditch on the East side (Soil Context 1) with one pottery sherd and cattle tooth (G-I, 1-3), a soil layer in the central section (Soil Context 2 and 3) with 226 pottery sherds and 21 pieces of coal and cinder (D-F, 1-3), and an accumulation on the West side (Soil Context 3) of 18 pottery sherds in the ditch fill and a topsoil containing 710 medieval pottery sherds, 6 ceramic building fragments, 8 pieces of coal and field waste, and 2 fragments of a waste pipe (A-C, 1-3).

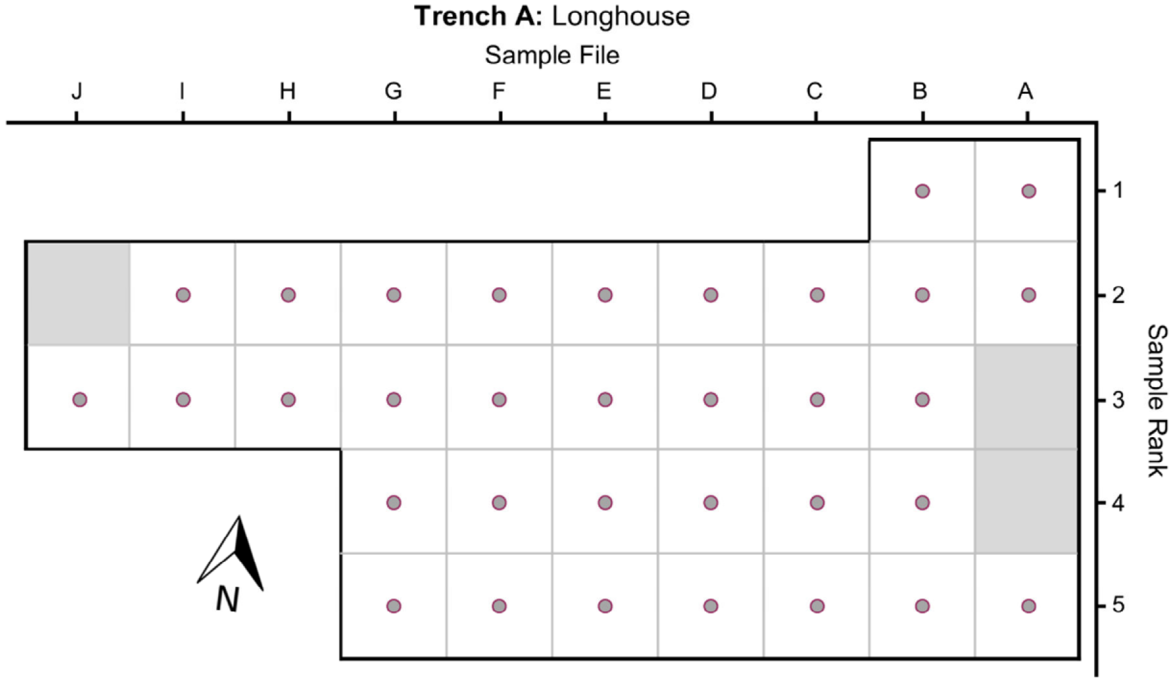

Figure 1: Trench A viewed from the East (A) toward the West (J), followed by the sampling plan. This Trench was sampled for pXRF after further excavation of the topsoil. Image courtesy of Tees Archaeology.

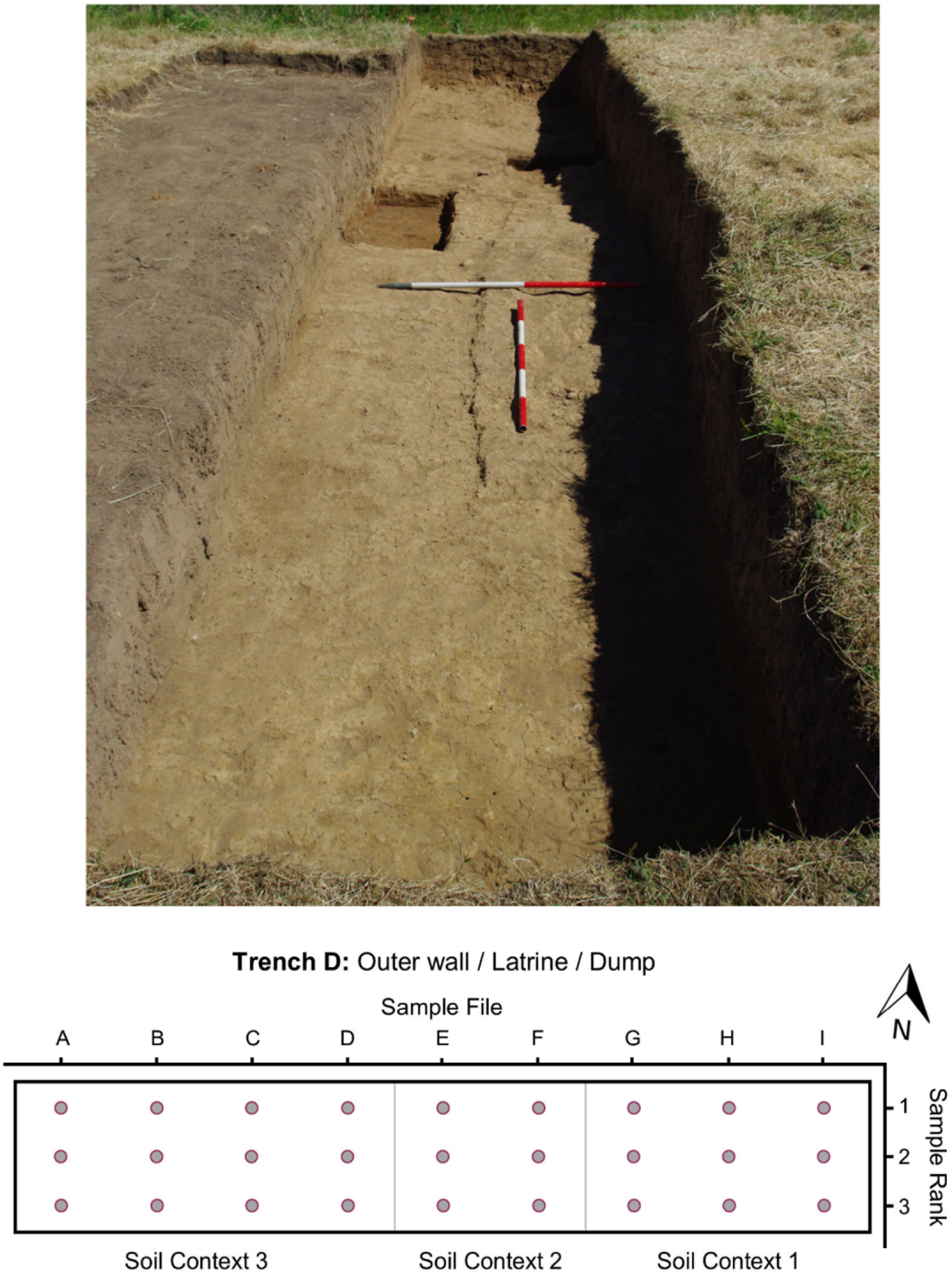

Figure 2: Trench D, viewed from the West (A) toward the East (I), followed by the sampling plan. The photograph shows the trench at the end of excavation and pXRF sampling. Image courtesy of Tees Archaeology.

The ex-situ pXRF soil analysis method developed by Williams *et al.* (2020) was followed: soil was oven-dried overnight at 105 °C, homogenised with mortar and pestle for 140 seconds, and sieved to 2 mm. Prepared soil samples were loaded into XRF sample cups (SPEX CertiPrep™ 3529) and covered with 5 µm polypropylene thin-film (SPEX™ SamplePrep 3520 window film). The pXRF (Thermo Niton™ XL3t GOLDD+ pXRF with an Ag anode; 6-50kV, 0-200 µA max X-ray tube) was warmed up, system checked, and tested against a blank and NIST 2709a standard reference material (SRM) to confirm that the internal calibration of the pXRF was performing correctly ($y=0.9674x -0.0078$, $r^2 = 0.9998$ after 25 test scans; full results included in the supplementary data). NIST 2709a is intended primarily as a reference for soil and sediment analysis. The SRM was not used to alter the internal calibration factor of the pXRF, and a site-specific SRM was not developed. NIST 2709a is certified for: Mg, Al, Si, P, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Rb, Sr, Zr, Cd, Sb, Ba and Pb. The NIST 2709a is a San Joaquin soil but was used because it was certified for most elements of interest within the single calibration sample (results were within the 20 % precision range certified by NIST 2709a).

The pXRF was periodically reset and system checked to account for drift. Samples were analysed using the Mining setting (Fundamental Parameters), with 30-second scans for the main filter (50 kV, ≤50 µA), low filter (20 kV, ≤100 µA), high filter (50 kV, ≤40 µA), and a 60-second scan for the light filter (6 kV, ≤200 µA). Analyses were performed in triplicate to provide the central tendency of the elemental concentration detected for each sampled location. The distribution of Mg, Al, Si, P, S, K, Ca, Mn, Fe and Au were targeted for interpretation.

3. Results

The median concentration (normality and variance assumptions failed) of each targeted element was plotted onto separate elemental maps using the *geom_raster* function of *ggplot2* (Wickham, 2016) in R 4.0.2 (R Core Team, 2020). The median concentration was set as the colouring midpoint, with "red", "orange" and "yellow" set as the highest, middle and lowest concentrations respectively. Raw values were used to identify distinct changes across the same soil surface, whereas additional normalisation would disguise the distinctions. The heat map layout was coordinated to simulate the sampling strategy plan (Figure 3 for heat maps from Trench A and Figure 4 for Trench D).

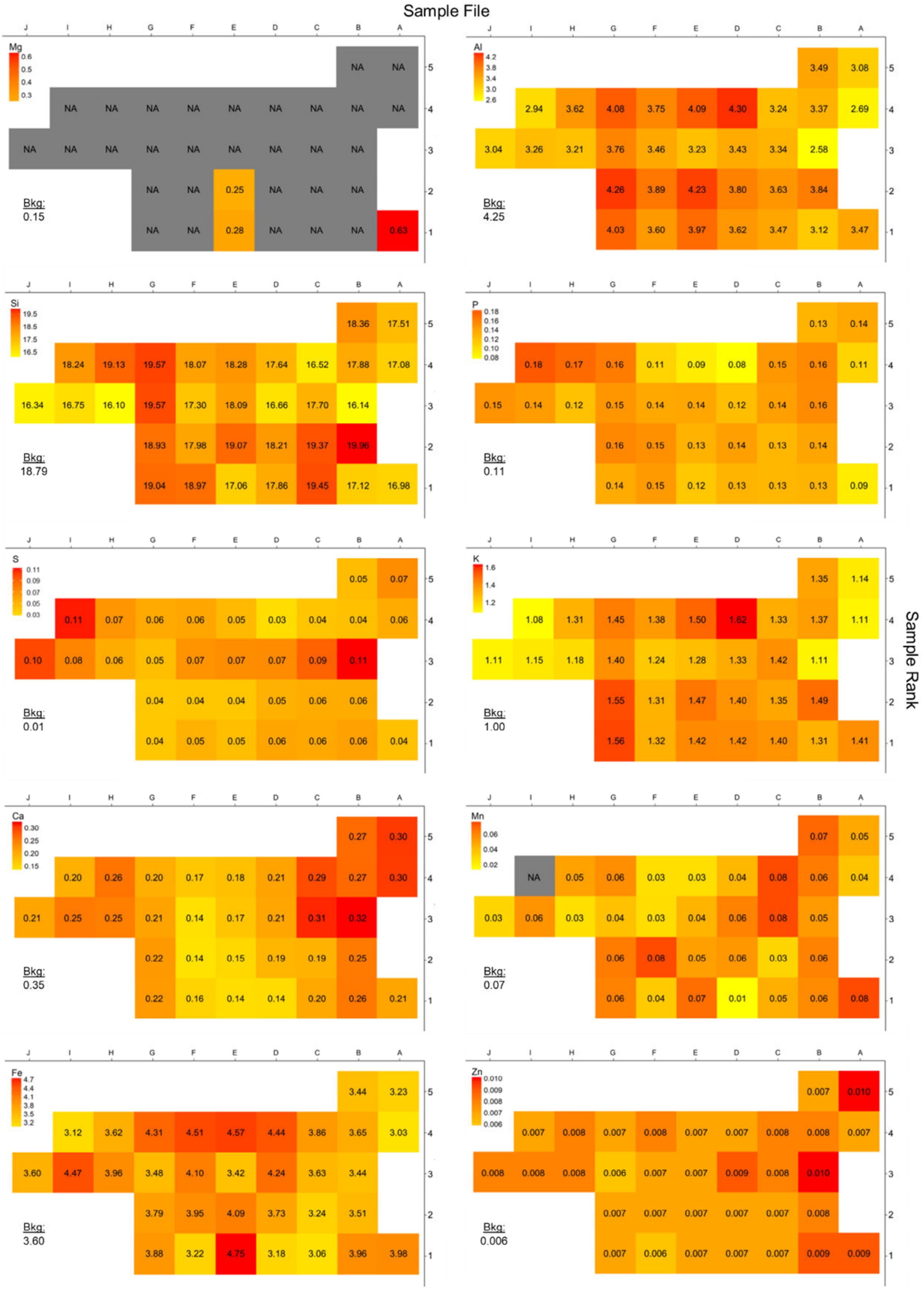

Figure 3: Collation of elemental heat maps from Trench A. Elements from left to right include: Mg, Al, Si, P, S, K, Ca, Mn, Fe, and Zn. Au is not provided because it was below the limit of sensitivity for all locations. NA denotes below detection limits. Background concentration provided (Bkg). Sample locations are coloured according to the intensity of the elemental distributions; numeric values of concentrations are also provided (%).

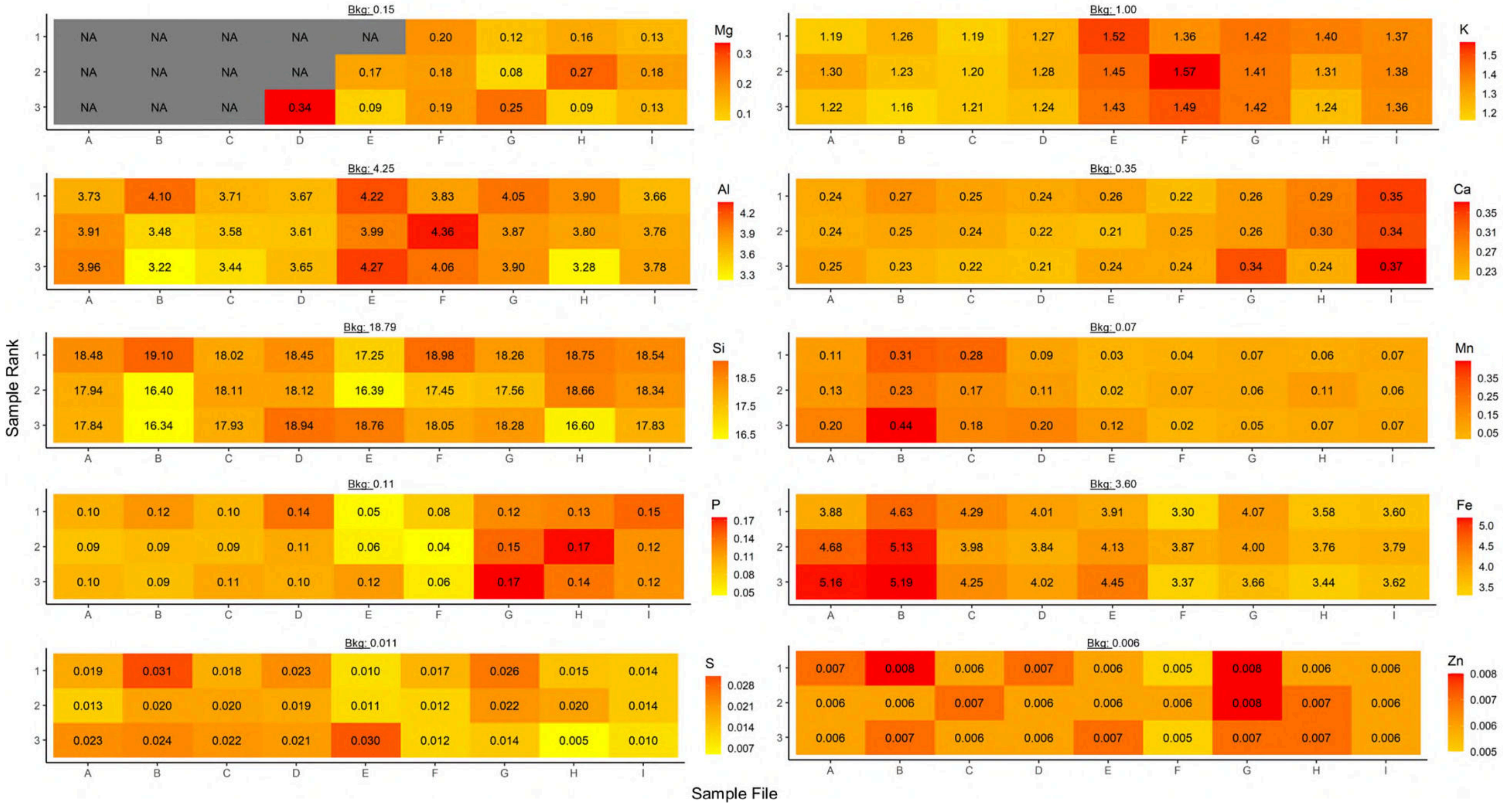

Figure 4: Collation of elemental heat maps from Trench D at Boroughgate. Elements from top to bottom include: Mg, Al, Si, P, S, K, Ca, Mn, Fe, and Zn. Background concentration provided (Bkg). Sample locations are coloured according to the intensity of the elemental distributions; numeric values of concentrations are also provided (%).

4. Elemental Interpretations

4.1. Magnesium

Magnesium has limited and contradicting application when interpreting archaeological soil. Konrad *et al.* (1983) associated magnesium with areas of intense burning. However, magnesium is unstable and easily affected by micro-environmental conditions, resulting in poor correlations with burning and activity areas (Gall, 2012; Pogue, 1988). Magnesium was frequently below detection limits at Boroughgate and showed substantial error for the few successful detections. This is largely due to the detection limits of magnesium with pXRF, particularly without a helium purge to account for the signal attenuation through air (Misra *et al.*, 2014). Gall (2012) also observed magnesium as the least useful predictor for locating activity areas. However, magnesium can indicate heavy disposal of organic material (Vranová *et al.*, 2015). The West of Trench D was entirely below detection limits whereas the East showed concentrations of 0.08-0.34 %. These detections may indicate organic and household waste and ash-tipping, supporting suggestions of this zone being a refuse site (Sulas *et al.*, 2019; Vranová *et al.*, 2015; Gall, 2012; Pogue, 1988). This is particularly interesting considering the iron content in the West section of Trench D may relate to butchery and burning (Cook *et al.*, 2006; Middleton, 2004; Terry *et al.*, 2004).

4.2. Phosphorus

Phosphorus is a minor component of many soil types by human occupation can raise phosphorus concentrations to major component levels over an extensive burial period (Linderholm, 2010; Rapp and Hill, 1999, p. 122). Phosphorus can identify human activity areas and manuring practices (Nielsen and Kristiansen, 2014; Migliavacca *et al.*, 2013), cultural features (Gall, 2012), delimit burial zones in graveyards (Cannell *et al.*, 2018), and show the intensity of previous human activities (Holliday and Gartner, 2007). Some forms of phosphorus also have limited mobility compared to other elements when in acidic soils such as at Boroughgate (Linderholm, 2010), which makes phosphorus essential for spatial archaeological research by delimiting boundaries of several anthropogenic activities. Eidt (1984, p. 41–43) showed that moderate phosphorus content, generally within 0.02-0.20 %, indicated dwellings and manufacturing areas. Eidt (1984, p. 41–43) also stated that burials have substantially higher phosphorus content, generally over 2 %, due to the leaching of phosphorus (and other elements) from decomposing remains into the soil (Holliday and Gartner, 2007; Turner-Walker, 2007; Trueman *et al.*, 2004; Rapp and Hill, 1999, p. 122; Eidt, 1984, p. 41–43). Refuse with substantial organic content such as food and human waste also leach phosphorus into soil (Vranová *et al.*, 2015). However, these values should be used as a general guide due to natural variation in soil, wherein some burials may have a phosphorus content unenhanced over the natural variation of phosphorus and some dwellings or settlements may have an exceptionally enhanced phosphorus content without burials (Holliday and Gartner, 2007; Heckenberger *et al.*, 1999). Trench A showed a phosphorus content between 0.08 and 0.18 %, but with a distinct inner zone consistently within 0.12 and 0.15 %, suggesting an internal and external divide. The associations between phosphorus and refuse also resulted in distinct refuse zones in Trench D that corroborated with Soil Context 1-3. The zones may have been used for separate purposes, such as the Eastern section (phosphorus files G-I) being the primary refuse site of the trench.

4.3. Sulphur

Sulphur does not identify anthropogenic activity well, but the low sulphur content encountered at Boroughgate is usually associated with good preservation, whereas high sulphur content can rapidly corrode metal artefacts (Kibblewhite *et al.*, 2015). The sulphur content of Trench A (Figure 3) showed no distinguishable features. The sulphur of Trench D (Figure 4) was below half of Trench A but showed some distinguished sections as with phosphorus content. More fragments of pottery were recovered from Trench D than Trench A, supporting the suggestion that Trench D was the primary refuse site with better preservation (Errickson *et al.*, 2017; Kibblewhite *et al.*, 2015).

4.4. Potassium

Potassium is frequently abundant in archaeological soils (Oonk *et al.*, 2009), particularly in deposits with high organic clay mineral content and ash content (Cuenca-García, 2019; Canti, 2003). The conflict of clean internal areas, manured sediment and ash-tipping from potassium (Fleisher and Sulas, 2015; Nielsen and Kristiansen, 2014; Pogue, 1988) was observed when Trench A displayed internal zoning from high potassium content (matching phosphorus and aluminium), but also an incline from 1.24 to 1.42 % potassium content toward the Eastern (refuse-rich) half of Trench D. The reduced mobility of potassium, particularly in the clayey soils at Boroughgate, distinguished internal and external areas better than zinc, phosphorus and calcium (Oonk *et al.*, 2009; Pratt, 1984), although the conflicting associations of potassium compared to the robust anthropogenic source of phosphorus limited its interpretive value.

4.5. Calcium

Calcium is present in animal bone, and may relate to carcass processing or food consumption (Pogue, 1988). Therefore, a high calcium content can identify food preparation and disposal areas (particularly middens), whereas clean areas of domestic buildings show low calcium (Vranová *et al.*, 2015; Middleton, 2004). Calcium was particularly useful because the archaeological team expected skeletal material but suggested that diagenetic processes resulted in their destruction, whereas the low calcium content of 0.14-0.37 % showed that skeletal assemblages were not previously buried and leached into the soil. Considering these associations of calcium, the South West area of Trench A without enhancement was a clean area of the longhouse, whereas the North East zone had double the calcium, indicating a likely refuse or food preparation area (Vranová *et al.*, 2015; Middleton, 2004; Pogue, 1988). These zones may evidence the baker, butcher or innkeeper reported in the medieval documentation (Errickson *et al.*, 2017). Trench D showed a 50 % spike in calcium accumulating toward the East, supporting this as a primary refuse zone. However, calcium was not as reliable an indicator as phosphorus due to its higher mobility, demonstrated by the drift of calcium compared to the clear zones of phosphorus (Linderholm, 2010; Oonk *et al.*, 2009; Pogue, 1988).

4.6. Iron

The variation of iron in soil can aid interpretations, such as identifying areas for burning charcoal (Middleton, 2004) or potentially identifying animal butchery and agave processing (Cook *et al.*, 2006; Manzanilla, 1996). Iron has been used alongside manganese, copper and lead to identify paint colours used on buildings and artwork (Musílek *et al.*, 2012; Terry *et al.*, 2004; Wells *et al.*, 2000). Care is required when applying these interpretations to Boroughgate due to several of these studies focusing around Guatemalan sites, and the potential variation in iron content caused by drainage and climate. Due to the ironstone and documentation of butchery at

Boroughgate (Errickson *et al.*, 2017), the high iron content was expected. The dispersed distribution of iron across Trench A made identifying activity zones difficult, although the high iron through Sample Rank 4 (Figure 3) may contribute to the bordering of the internal area identified by phosphorus. Wilson *et al.* (2008) also observed little distinction in iron (and aluminium) content for distinguishing functional areas, whereas the 26 other elements they observed were enhanced between different farms. Trench D showed a clear, gradual increase in iron content rising from the East toward the West, which may relate to the nature of the refuse site, may support indications by magnesium of burning and butchery (Cook *et al.*, 2006; Middleton, 2004; Terry *et al.*, 2004), or just be evidence of the probable erosion that started on the East side of Trench D.

4.7. Elements with Limited Interpretive Value

Silicon is the main inorganic component of soil, making the distinction of an anthropogenic elemental fingerprint unlikely (Bojórquez-Quintal *et al.*, 2017; Wilson *et al.*, 2008). Silicon also lacks direct associations with activity (Wilson *et al.*, 2008). These features were observed by the indistinguishable zones in both trenches.

Aluminium dominates the elemental composition of soil and forms a substantial part of baseline geology, limiting its use in surveying and mapping a site (Bojórquez-Quintal *et al.*, 2017; Cook *et al.*, 2006). Aluminium also has little association with identifying anthropogenic activities (Wilson *et al.*, 2005). Regardless, high concentrations detected at Boroughgate approximately mirrored the clean and refuse zones observed with calcium content, supporting the potential inclusion of aluminium in future investigations. Detecting aluminium had little value for interpreting anthropogenic activity but may be more relevant for studies investigating preservation due to the toxicity of aluminium toward microorganisms, thus potentially inhibiting diagenesis (Levett *et al.*, 2019).

High chlorine content can inform conservation processes due to the need for desalination before drying (Réguer *et al.*, 2007). Chlorine was below detection limits throughout Boroughgate, suggesting that desalination and corrosion were not concerns, although chlorine salts are rapidly leached from soils in non-arid climates. However, chlorine is difficult to reliably detect because it is near the pXRF detection limits and requires a helium purge for analytical reliability (Misra *et al.*, 2014), therefore is unlikely to be routinely useful for informing conservation.

Manganese may indicate activity areas and structures alongside phosphorus, mostly due to its use in archaeological paint production (Gall, 2012; Terry *et al.*, 2004; Wells *et al.*, 2000). However, manganese showed no consistent patterns in Trench A to support interpretations, although the sharp incline from 0.06 to 0.44 % toward the Western portion of Trench D may support indications of an active refuse disposal zone.

Zinc leaches into soil following burning and decay of organic refuse (Oonk *et al.*, 2009; Wilson *et al.*, 2008; Entwistle *et al.*, 2000). Zinc showed zoning patterns similar to phosphorus (0.007% for most of Trench A internal area) but was unreliable due to low concentrations and inconsistent variation across Trench A (0.006-0.010 %) and Trench D (0.005-0.008 %).

The rarity of precious metals in soil means that detecting traces in burial environments with no naturogenic source may indicate anthropogenic activity (Wilson *et al.*, 2008; Holliday, 2004). For example, Cannell *et al.* (2020) observed substantial leaching of elements relating to metalworking in the later phases of Heimdalsjordet, Norway, and elemental maps of precious metals by Sylvester *et al.* (2017) delineated around the known areas of metalworking at St. Algar's Farm, Somerset UK. However, the small size of jewellery compared to the burial environment, and low volume of trade and metal working at Boroughgate, means that detecting traces of gold and other precious metals from the soil survey was unlikely. Consequently, gold was below the limits of detection for every analysis despite the documentation of a goldbeater (Errickson *et al.*, 2017). Artefact evidence would be more appropriate and conclusive in supporting this activity.

4.8. Archaeological behaviours with combined elemental interpretation zones

Individual elemental assessments were combined with artefact finds maps to provide the summarised interpretations in Figure 5 (Trench A) and Figure 6 (Trench D) and support the archaeological team. The presence of a household indicated by phosphorus and calcium in Trench A corroborated with the presence of postholes, daub and building fragments. The zones of aluminium, phosphorus, potassium, calcium and iron suggested an internal and external divide, of which the boundaries aligned with the building foundation pads in the centre (internal) and bordering of postholes and wall foundations (external). Most pottery fragments and daub also accumulated in the external area, represented by increased magnesium and calcium content compared to the internal zone. The boundaries of aluminium, potassium and calcium identified potential clean and refuse areas in the absence of sufficient archaeological evidence beyond the small amounts of domestic and charred waste in these areas. The distinction of separate zones reflects the assessment by Macphail and Goldberg (2018) where household floors with few remains are caused by frequent sweeping and relocation of waste material being discarded elsewhere (Mateu *et al.*, 2019). Overall, chemical analysis of Trench A corroborated well with the archaeological interpretations, supporting human presence and identifying potential zones for activities or internal areas (Adams and Daniels, 2019, p. 26; Williams and Taylor, 2019).

Trench D was difficult to interpret because the limited range of material discovered and re-cut of the fill and topsoil obscured the original archaeological deposit. The heat mapped refuse zones of magnesium, phosphorus, potassium, calcium, manganese and iron content (Figure 4) corroborated with the three soil contexts identified by the archaeological team and sampling plan. The larger concentration of phosphorus, potassium and calcium in Soil Context 1 indicated this as the primary deposit site, which supported the excavation report of Soil Context 1 being the earliest deposit in this trench due to the probable erosion in the East boundary (Adams and Daniels, 2019, p. 16). Whilst the use of magnesium and manganese for indicating burning refuse was considered unreliable, these elements were presented within the locality of coal and cinder in Soil Contexts 1 and 3. Overall, the elemental distribution of Trench D suggested zones of refuse and burnt waste disposal. The elemental zones matched the three soil contexts within one mostly contemporaneous stratigraphy but did not fully corroborate with the archaeological interpretation. They instead proposed that the large portion of pottery sherds and several animal bone fragments in Trench D may relate to cuts, re-cuts, infilling and animal occupation rather than designated refuse areas (Adams and Daniels, 2019, p. 26). This application of pXRF is novel and evolving, with currently limited ability in interpreting and categorising elemental interpretations, particularly with the complexity of geochemistry, soil processes and unrealistic thresholds. Therefore, this elemental distribution may be more supportive of the interpretation of accumulated material, animal occupation and redeposits.

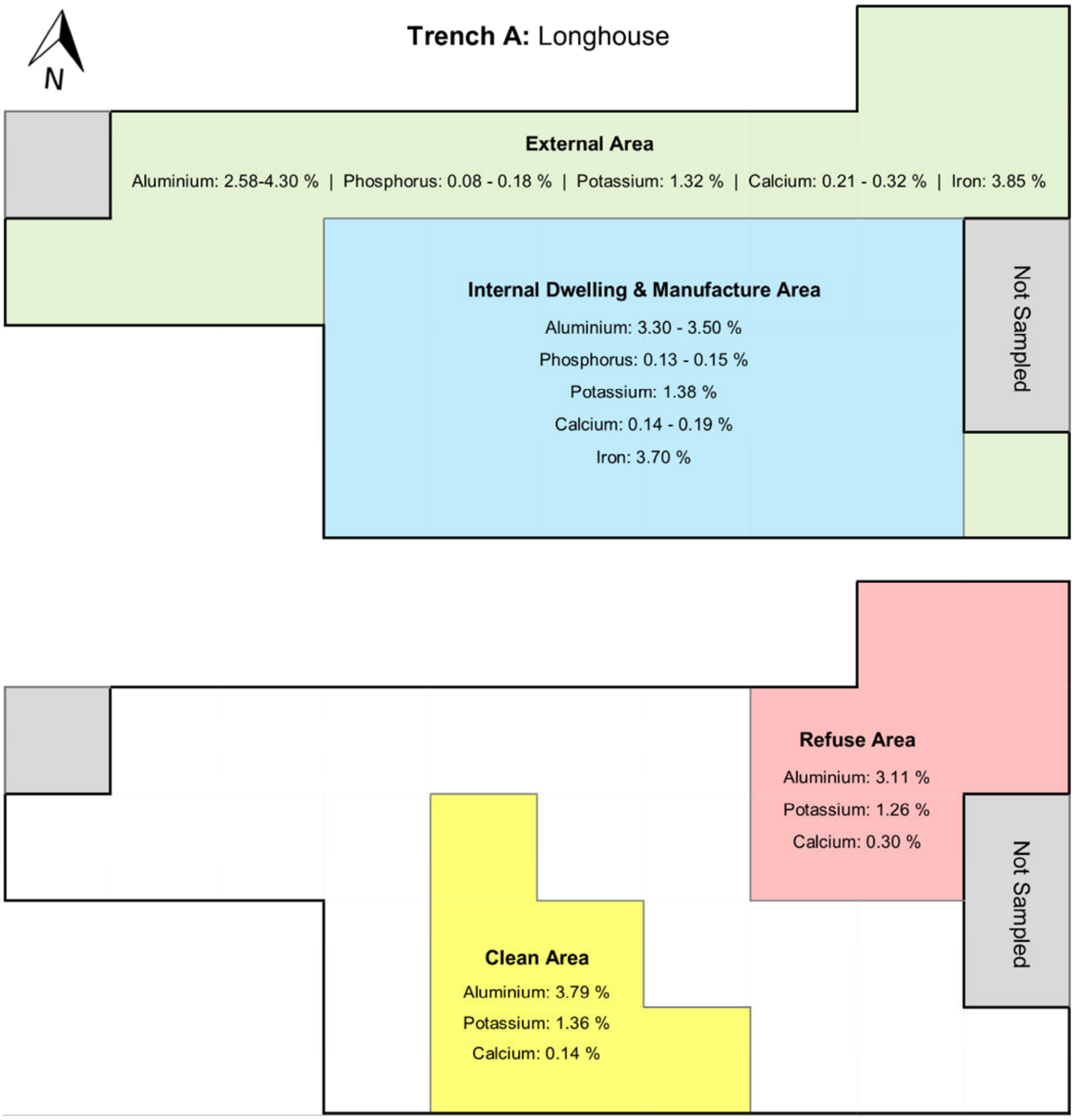

Figure 5: Interpretation of Trench A, distinguishing internal and external zones, followed by clean and refuse zones. Median values or concentration ranges of the elements used are provided.

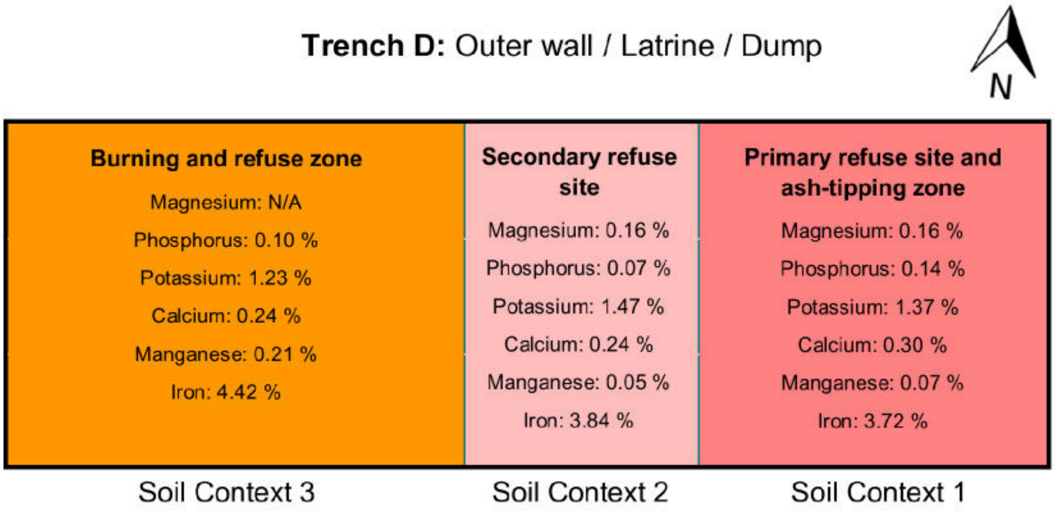

Figure 6: Interpretation of Trench D, distinguishing refuse and *potential* burning zones. These zones matched the three soil contexts identified by the excavation team. Median concentrations provided.

4.9. Considerations for Elemental Mapping with pXRF

Comparing elemental concentrations of different soil samples would be inappropriate if samples were inconsistent due to using mixed or simple preparation protocols (Williams *et al.*, 2020). For example, moisture content may be different across soil contexts, resulting in significantly different elemental concentrations and identified activity zones due to attenuation of X-rays by moisture (Williams *et al.*, 2020; Stockmann *et al.*, 2016). Full ex-situ preparation was therefore required for reliable mapping by minimising the impact of soil matrix effects between samples (Williams *et al.*, 2020; Luo and Bathurst, 2017). This ensured consistency without requiring bespoke correction factors (Tian *et al.*, 2018; Maruyama *et al.*, 2008). Comparing individual sites closely, and specifying a precise activity or action, are also quick ways to misinterpret a site (Wilson *et al.*, 2009). Using wide concentration boundaries to delimit general zone divisions reduced this subjectivity without being too liberal or specific.

Kriging is a common method encountered in interpolation, mapping and spatial analysis. However, kriging and other GIS techniques were inappropriate for this investigation at Boroughgate. All locations in Trench A and D were sampled, effectively meaning that there were no unknown data points to krig (Gupta, 2020; Lloyd and Atkinson, 2004). The sample areas were small and irregularly shaped, preventing the kriging from estimating large areas between individually weighted data points (Bevan, 2020; Conolly, 2020; Lloyd and Atkinson, 2004). This also produced accentuated spikes in elemental concentration between adjacent sample locations due to attempts in kriging discreet locations between evenly weighted data (Conolly, 2020), thus artificially emphasising additional activity zones. In contrast, *ggplot2* reported data without any grouping or estimation for a more exact representation, with applicability to the small excavation areas in both Trench A and Trench D. Where kriging and GIS analyses had low effectiveness for mapping activity at Boroughgate, they would prove useful in site-wide analyses.

5. Conclusion

This investigation successfully demonstrated the potential for pXRF as an archaeological technique for enhancing and supporting the survey and interpretation capabilities of an excavation. The use of pXRF soil analysis at Boroughgate produced heat maps that summarised elemental distribution with low cost and time requirements. These heat maps distinguished zones in the Trench A longhouse, including internal or external areas, and clean or refuse areas. Trench D also showed zones likely used for refuse and burning waste. The resulting combination of these heat maps provided simplified and visually appealing summary maps that supported and enhanced the interpretations made by the excavation team for Trench A. Trench D proposed some alternative interpretations which may corroborate well with the archaeology, but data from more sites are needed for comparisons. Additional archaeological evidence would be required for providing a full interpretation of the site, particularly if determining between living and manufacturing uses. These interpretations are specific to the site at Boroughgate or sites with very similar conditions due to soil variation. Whilst the recommended interpretations will be useful to future applications on other archaeological sites, caution must be taken not to over-interpret and sensationalise the evidence particularly if using unrealistic threshold values that may ignore the complexity of geochemistry. This research forms a basis for future applications of mapping for large and small-scale sites. The understanding of soils, chemical processes, and the influence of human activity on these may be improved as more environments are analysed and mapped in this style alongside further geochemical research.

6. Declarations

Availability of data and material: The data that supports the findings of this study are available in the supplementary material of this article

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7. References

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