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RESEARCH

Soil investigations to determine the function of different areas within the Roman fortress near Hermeskeil (Germany)

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Abstract

The area of the Hermeskeil main camp, built by the Roman army during Caesar's Gallic Wars, is subdivided by an internal fortification consisting of a ditch and bank and separating a larger southern from a smaller northern part of the fortress. Our study deals with possible functional differences between these two parts of the temporary camp since both a separate stationing of potentially mounted auxilia and a secondary reduction of the camp's surface could explain the building of such internal defences. An intensive soil survey was undertaken in the northern part of the main camp to delineate areas of high human activity. We conducted a mapping of 128 drill cores. Multi-element analyses and their statistical evaluation succeeded in isolating anthropogenically influenced areas, which were, however, located exclusively in the *intervallum*, i.e. the space immediately behind the camp's ditch and bank that was left free of housing regular troop quarters. Samples in this area also showed a high coprostanol/cholestanol and a low 5β-stigmastanol/coprostanol ratio, indicating faecal matter from omnivores. Biomarker analyses do not indicate that horses and, therefore, auxilia were present in the northern part of the main camp, but the ratios of individual biomarkers rather speak in favour of the existence of latrines in the *intervallum*. Accordingly, the northern part of the Hermeskeil main camp was probably used for the regular stationing of infantry. The building of an internal fortification, therefore, most probably relates to a secondary reduction of its surface, which was connected to a phase of re-use.

Keywords Multi-element mapping · Faecal marker · Julius Caesar · Gallic wars

Introduction

Since humans have interfered with the natural environment, it has undergone significant changes (Roberts 2019), which are evident in the soil. Soils are seen as witnesses to the natural and cultural development of a landscape (Vanwalleghem et al. 2017). Human activity changes physical and chemical properties of soil and their natural development (Šmejda et al. 2018). These changes can often still be seen in the present, even if they occurred a long time ago (Dirix et al. 2013; Parnell et al. 2002).

The study by Arrhenius, who was the first to recognize the direct link between old farmsteads, settlements and phosphorus (P) accumulation in soils, was trendsetting (Arrhenius 1931). Myriads of studies followed, impressively showing that P is a powerful indicator of human habitation and activity areas (Salisbury 2020; Entwistle et al. 2000; Oonk et al. 2009a). Since the end of the 20th century, a trend away from single P-analysis to multi-element analysis (Entwistle and Abrahams 1997; Oonk et al. 2009a;

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Nielsen and Kristiansen 2014; Middleton and Price 1996), as well as from non-quantitative field tests to the application of high-precision laboratory techniques, can be observed (Šmejda et al. 2018; Wilson et al. 2008; Nielsen and Kristiansen 2014). As a rule, elements for determining anthropogenic activity on ancient sites are P, Ca, K, Na and Mg, as are the trace elements Cd, Cr, Cu, Pb and Zn (Oonk et al. 2009a; Vyncke et al. 2011; Parnell et al. 2002). Through this it could be shown that there is no single element that provides a unique signature for a particular activity domain, but rather a combination of different elements (Wilson et al. 2005). Today, multi-elemental analysis of soils is a common component of archaeological excavations and surface investigations (Bintliff and Degryse 2022; Vyncke et al. 2011).

However, the geochemical fingerprint of anthropogenic elements often does not suffice to detect and identify archaeological soils (Oonk et al. 2009a). In this case, a combination of multi-elemental and lipid analyses may provide insight (Hjulström and Isaksson 2009; Kanthilatha et al. 2014). Lipids (steroids) are (i) more resistant to degradation than other molecular classes (e.g. proteins, nucleic acids), allowing long-term preservation; (ii) have a large variety of chemical structures that can be taxonomically and physiologically diagnostic (Pearson 2018); and (iii) are hydrophobic and insoluble in water that prevents leaching (Lloyd et al. 2016). Based on their properties, lipids are considered to be biomarkers.

This has made it possible to unambiguously identify, for example, animal processing facilities by fatty acids (Butler et al. 2018) and cholesterol (Middleton et al. 2010), middens and hearths through fatty acids (Kedrowski et al. 2009), latrines and anthropogenic soil formation by coprostanol (Baeten et al. 2012; Birk et al. 2012). Biomarkers are still only rarely used in archaeological contexts, although they could open up new interpretive potentials in dealing with archaeological sites. This is especially true in cases where geophysical surveys or regular excavations are hindered (Brown et al. 2021). For these reasons, soil prospection and analyses played a key role in the archaeological investigation of the Hermeskeil fortress, a site from the time of Caesar's Gallic Wars (58–51 BC) and, as yet, the only securely dated temporary camp from these campaigns (Hornung 2018, 2019). The western part of the military camp lies in arable land where geophysical prospections as well as targeted excavations, focusing mainly on neuralgic points in the camp's defences and several field ovens in its interior, were conducted between 2010 and 2020. In contrast, the eastern part of the site is densely forested, leaving only-limited options for conventional archaeological investigation (Hornung 2024).

Covering a total surface of 30.7 ha, the Hermeskeil fortress consists of a square main camp (19.5 ha) and an annex attached to its north-western side (11.2 ha), which also enclosed a well securing water supply. Both parts of the fortress were protected by a V-shaped ditch and an adjacent bank built with material from the excavated ditch and stabilized by turves. Another fortification of a ditch and bank subdivided the interior of the main camp, partitioning its northern part (7.3 ha) from a larger southern part (12.2 ha) and raising questions as to the exact function of these two separate areas within the main camp. Two alternative explanations for the existence of an interior fortification had to be considered:

1) A secondary reduction in size of the main camp in some subsequent Roman campaign, reflecting a common practice in Roman military context and best explained by a strategic choice of location. A number of Imperial-period temporary camps from Britain structurally resemble the Hermeskeil findings, e.g. Cornhill I/II, Inchtuthil I/II, Ulston Moor I/II, Uffington I/II, Kinvaston, Haltwhistle Burn II/III or Seatsides I, where three sides of the camp fortifications are two-phased and only an internal ditch and bank attest a secondary adaptation in size (Hornung 2024; Jones 2011, 2012). The same practice is known from the Marcomannic Wars, e.g. at Mušov / "Na piskach" (Komoróczy et al. 2020), and possibly even from the Caesarian period at Mirebeau-sur-Bèze / "La Fenotte" (Reddé et al. 2006).
2) The internal ditch and bank could also have separated Roman legionaries from allied troops that had proven not entirely trustworthy during Caesar's conquest and may, therefore, have been accommodated separately. Since the annex is another feature of the Hermeskeil fortress most probably relating to the stationing of auxiliaries, a presence of cavalry units in the northern part of the main camp has to be considered the most plausible option for explaining an additional bipartite structure of the main camp. It would be well in line with the information given by historical sources which mention Germanic cavalry operating with the Roman legions during the Gallic Wars (Labisch 1975b). Moreover, their presence may also be suggested by two finds from the Hermeskeil main camp.

Archaeological structures in the interior of the main camp seemed inconclusive with regards to deciding between these two options and did not provide any basis for the identification of functional differences between both parts of the fortress. Field ovens used for baking and/or cooking, which were detected during geophysical surveys in the areas currently under plough and subsequently excavated, are known mainly from its southern part, but this area is generally less affected by erosion. Therefore, their distribution could well

reflect differences in preservation rather than function. Evidence for other facilities, for example latrines, was even missing completely.

Soil analysis, therefore, seemed the most promising method to attempt to answer the questions centred around the function of the northern part of the main camp, because the dense forest cover over its entire eastern area provided almost ideal conditions for sampling and at the same time hindered archaeological/geophysical investigations. Therefore, multi-element mapping was conducted in the northern part of the main camp, in order to identify areas with high human activity, whose exact nature could then be explored further by a complementary use of biomarker analyses. With the help of this combination of methods, two initial hypotheses – focusing on a possible use of the northern part of the main camp for cavalry units – were to be tested:

1) Considering the number of horses and people to be expected in the case of a separate stationing of allied cavalry, as well as an extended use of the camp over several weeks, a spatial accumulation of elements (especially P and organic carbon) within but not outside the separate northern part of the camp had to be expected.
2) Within these areas, increased element concentrations and faecal markers from herbivores (horses) and humans could be detected.

Materials and methods

Environmental setting

The study area around Hermeskeil is located in the Hunsrück, a low mountain range whose rocks are mainly (Lower) Devonian and were folded during the Variscan/Hercynian orogeny. Hermeskeil lies for the most part on red and green-grey clay slates, as well as siltstones and greenish, green and grey quartzites of the Züscher shale from the Obergedinne period. Immediately southeast of Hermeskeil was the layer boundary to the younger Hermeskeil layers from the Lower Siegen period. The Hermeskeil strata consist of green-grey, grey to blue-grey quartzites and clay shales, which take on a reddish colouration when more extremely weathered (Kneidl 2011; Reichert 1980). The study area lies within the boundary zone of the Züscher shale and the Hermeskeil strata. The initial substrate of soil formation was an association of sandstone, quartzites and shales owing to solifluction or alternating bedding.

The climate of the study site is humid temperate with warm summers (Cfb). The annual average temperature is 7.6 °C and the annual precipitation is 853 mm.

The Hermeskeil fortress is situated a little east of the modern town and occupies a low ridge (593–611.7 m above sea level), which slopes gently towards to west, but rather steeply into the adjacent valley of the River Prims towards the east. Thanks to this liminal setting, the eastern part of the fortress is still heavily wooded today and used for forestry, whereas the areas further to the west are under the plough. This resulted in differing conditions for the preservation of all archaeological remains.

Sampling and sample preparation

Our study focused on the currently forested area, because it is assumed to be less impacted by recent agricultural use (Fig. 1). Before we started mapping, we obtained an overview by digging a soil pit inside the camp. The existing soil horizon corresponds to that of a Cambisol (WRB 2015) and is characterized by acidic conditions (pH 3.6–4.5), low base saturation and a silt loamy texture (Online Resources 1).

In total, we took soil samples from 461 horizons at 128 drill points (including soil profiles) (Online Resources 2). Each position of sampling was determined by a total station (GPT-7003i Imaging Total Station, TOPCON SOUTH ASIA PTE LTD, Singapore). The sampling in the separate northern part of the main camp was carried out in a 25 × 25 m grid (= 87 drill points).

In addition, within this grid five drill cores were taken at two randomly selected locations ($n = 10$). Another 13 samples were taken along a cross-section through the camp's bank and the adjacent *intervallum* on its south-eastern side at 0.5 m intervals (Fig. 2). Outside the camp's fortifications, samples were taken northeast (outside main camp) and southwest of the separated northern part of the main camp (= 18 drill points). Ah-horizons of soils were sampled with a spade, B-horizons in 20 cm increments using an Edelmann drill. The massive C-horizons were not sampled. All samples were dried at 40 °C, sieved (≤ 2 mm) and homogenized using a ball mill (Planetary Ball Mill PM 200; Retsch GmbH, Hanau, Germany).

Multi-element soil analysis

Total carbon and nitrogen contents were determined by a C-N analyser (Vario EL CUBE; Elementar Analysensysteme GmbH, Langenselbold, Germany). Since the soils are carbonate-free, total carbon corresponds to that of total organic carbon (TOC).

The elements iron (Fe), barium (Ba), aluminum (Al), vanadium (V), cobalt (Co), nickel (Ni), potassium (K), sodium (Na), lithium (Li), copper (Cu), magnesium (Mg), manganese (Mn), zinc (Zn), chromium (Cr), calcium (Ca), titanium (Ti), phosphorus (P), lead (Pb), arsenic (As) and

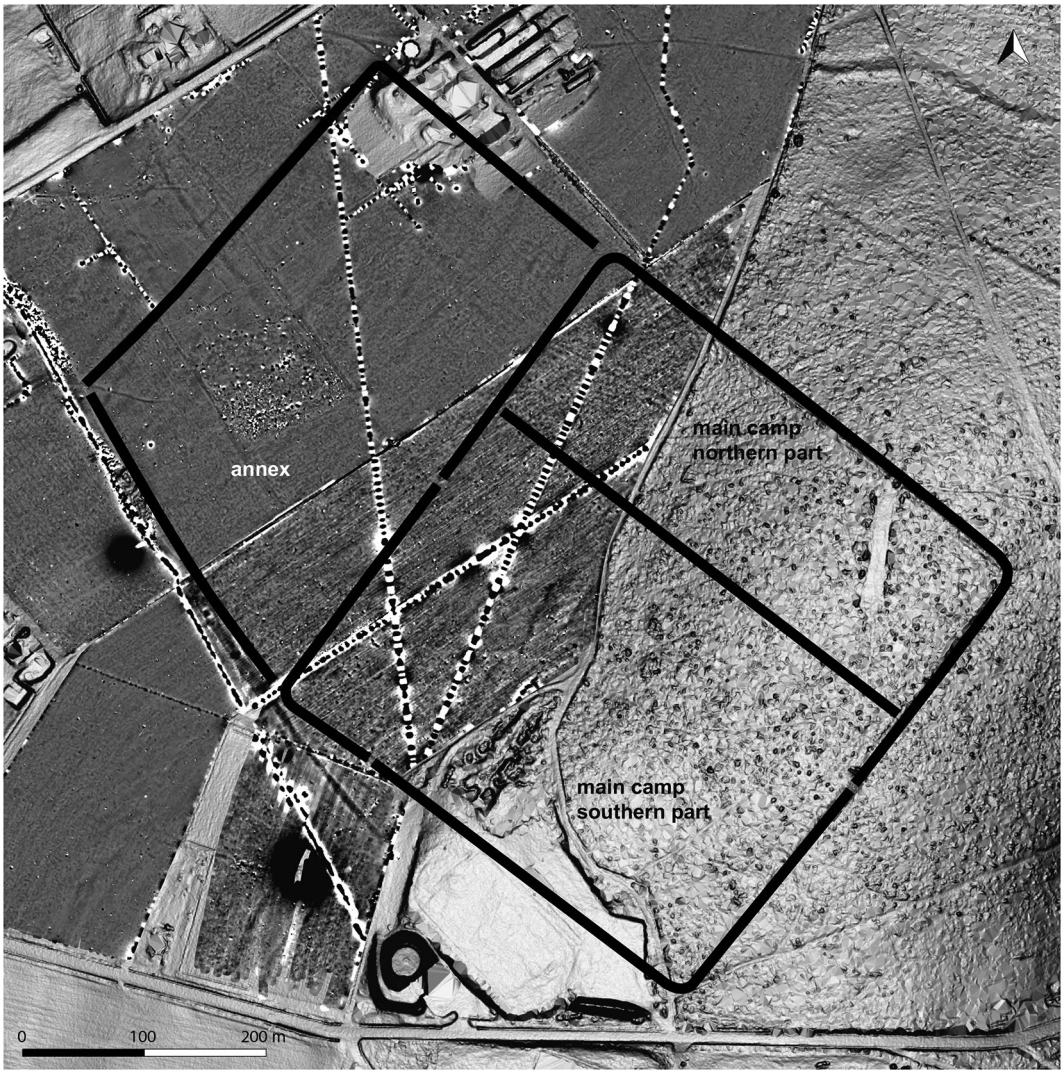

Fig. 1 Overview map of the Roman fortress near Hermeskeil (Germany)

strontium (Sr) were extracted by aqua regia (HNO_3 and HCl 3:1 v/v) in a microwave oven (Mars 5 Xpress, CEM GmbH, Kamp-Lintfort, Germany) and determined using optical emission spectrometry with inductively coupled plasma (ICP-OES; Ametec Spectro-Arcos, Kleve (Cleves), Germany). In contrast to hydrofluoric acid digestion, poorly soluble silicates (quartz and feldspar) are incompletely dissolved in aqua regia extraction (Schwartz and Kölbel 1992). It is, therefore, a 'pseudo-total' extraction. However, element inputs from the deposition of organic waste (e.g. food remains, faeces) should be fully recorded using this method.

Evaluation and processing of analysis data

To identify and summarize points with similar element contents, the concentrations of elements and TOC content of 304 subsoil samples were statistically evaluated with the statistics package SPSS 23 (IBM, Armonk, NY, USA). Topsoils (A-horizons) were influenced by modern-day activities and do not correspond to the relict occupation layer. Therefore, they were excluded from the evaluation. Nitrogen showed extremely low concentrations in the study area and was, therefore, also not included in the statistical analysis (Online Resources 2).

Factor analysis made it possible to classify the individual elements (variables) into groups within which element concentrations correlate. A new variable (latent variable represented by a factor, e.g. deposition of faeces) was extracted for each individual group, which summarizes the values of the individual element concentrations. The number of factors was chosen according to the Kaiser criterion, so that each factor had an eigenvalue of >1. Factors were rotated using the Varimax procedure with Kaiser normalisation to obtain factors and factor loadings that could be interpreted in terms of content. In this study, the factor loading of an element is a measure of the correlation between a factor

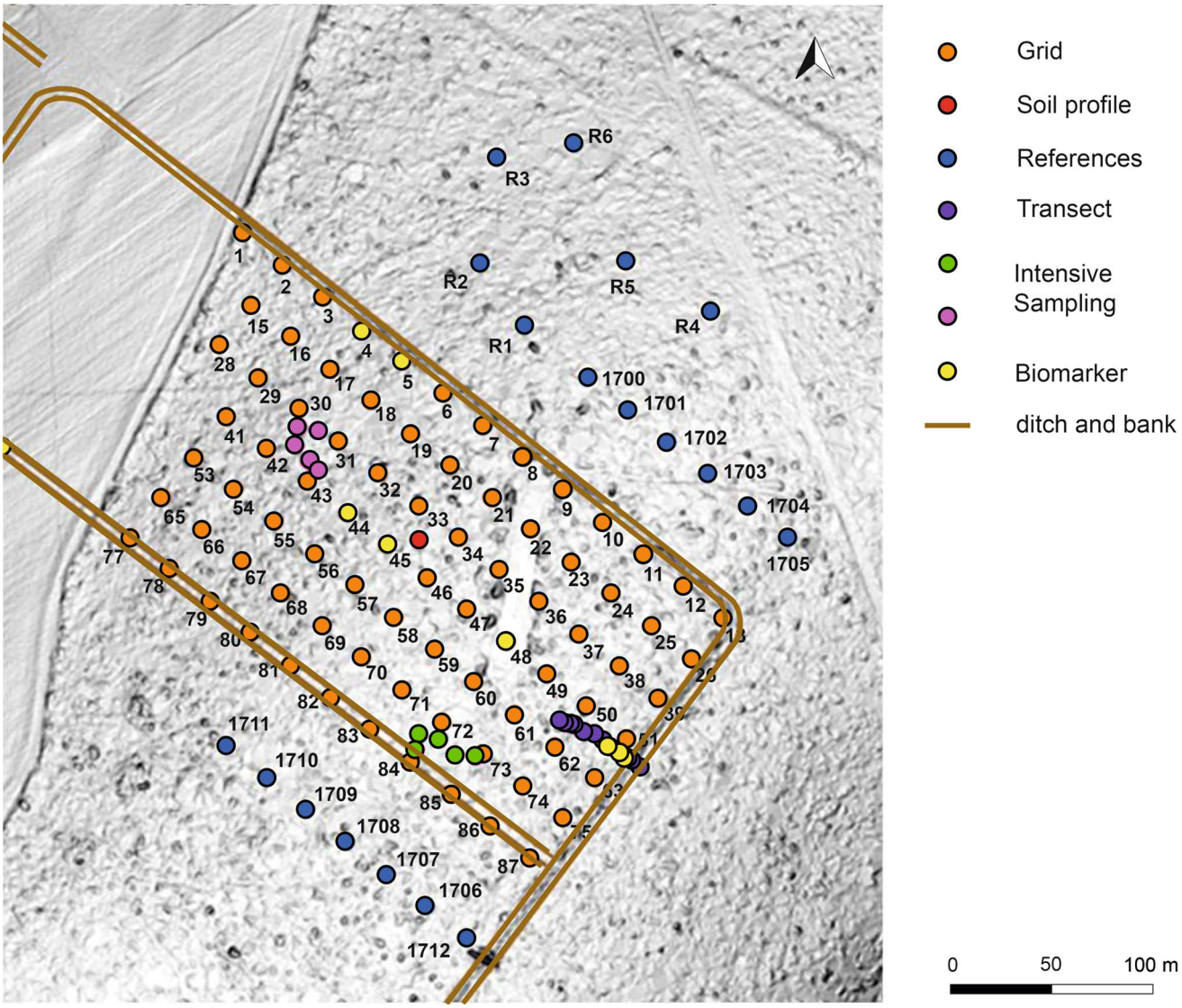

Fig. 2 Spatial distribution of sampling points in the northern part of the main camp and outside the Roman fortress near Hermeskeil

and element concentration. Factor values for individual samples were calculated by linear regression. A factor value for a single sample provides information on how high the element concentrations summarized in a factor are for this sample. The suitability of the data set for factor analysis was checked using the Kaiser-Meyer-Olkin measure and Bartlett's test for sphericity.

The factor scores were used to perform a hierarchical cluster analysis based on the unweighted variables using Ward's method. This successively merges factor scores and clusters, keeping heterogeneity within the clusters as minimal as possible (Schönwiese 2020). Heterogeneity was quantified by the sum of squared Euclidean distances. The number of clusters was chosen so that a further merger of clusters would have led to a sudden increase in heterogeneity (sum of squared errors) within the newly formed cluster.

A factorial analysis of variance was performed to investigate whether the means of the individual variables (factor scores, element concentrations) differed significantly between the clusters. The GT2 according to Hochberg and the Games-Howell test were calculated as post hoc tests. The GT2 assumes equality of variance within clusters, the Games-Howell test, on the other hand, does not (Janssen and Laatz 2007), but it is less sensitive than the GT2. Homogeneity of variances of all clusters was checked by means of Levene's test. Since many variables showed significantly different variances of the individual clusters, the decadic logarithm of these variables was calculated and the logarithmized values of the contents of P, As, and Pb could be evaluated using Hochberg's GT2. For all other variables, the data were tested without logarithmization using the

Games-Howell test. A significance level of $P \leq 0.05$ was set for all statistical tests.

Biomarker soil analysis

Sample selection for biomarker analysis was performed after statistical evaluation of multi-element analysis. A slightly modified method from Birk et al. (2012) was applied and a Soxhlet extraction of ground samples with dichloromethane and methanol (2:1. v/v) with subsequent saponification conducted. Using a liquid-liquid extraction, the biomarkers were extracted from the saponification solution, separating the stanols. The Δ^5-sterols and other substances with a similar or lower polarity were separated from more polar substances such as fatty acids. The stanols and Δ^5-sterols were purified by solid phase extraction (SPE) and separated from more non-polar substances. They were silylated with BSTFA+TMCS prior to measurement on a gas chromatograph coupled to mass spectrometry (5975B, 6890 N, column DB-5ms, Agilent, Santa Clara, CA, USA). Scan mode measurements were performed to verify peak identity and selected ion monitoring (SIM) mode measurements performed for quantification. External and internal standards were used for quantification (Online Resources 3).

Table 1 Factor loadings of the factor analysis (principal component analysis), as well as the explained variance of the respective factors. High factor loadings (defined here as > 0.5) indicate that the element concentrations and the respective factor show a strong correlation. The elements associated with a factor are highlighted in grey

Factor	1	2	3	4
Element	Factor loadings			
Fe	0.926	-0.077	0.058	-0.086
Ba	0.923	-0.164	-0.149	0.093
Al	0.908	-0.015	-0.179	0.082
V	0.882	-0.106	0.137	0.208
Co	0.877	-0.109	-0.025	-0.183
Ni	0.876	-0.188	-0.023	-0.100
K	0.863	-0.371	-0.141	0.038
Na	0.846	0.185	0.057	0.144
Li	0.819	0.159	0.172	-0.305
Cu	0.815	-0.129	0.165	-0.057
Mg	0.813	0.027	-0.274	0.169
Mn	0.767	0.205	0.059	-0.336
Zn	0.719	0.208	-0.146	0.171
Cr	0.595	-0.520	0.001	0.298
Ca	-0.103	0.867	0.176	0.122
Ti	0.002	0.858	0.059	0.317
P	0.173	0.645	0.554	-0.175
TOC	-0.212	0.276	0.831	-0.153
Pb	0.170	-0.005	0.823	0.042
As	-0.142	0.104	0.739	0.251
Sr	0.028	0.226	0.093	0.755
Explained variance (%)	47.1	12.9	12.0	0.6

Results and discussion

Soil mapping

The depth of soil formation (median) was 49 cm inside and 67 cm outside the camp. Along the cross-section the soil thickness varied between 25 (ditch) and 115 cm (bank).

With the exception of drill point 48, Cambisols were mapped on the study area. Some of these showed initial (transitional horizons Ah-Ae) or slightly pronounced podzolization (thin Ae-horizon). Significant redoximorphic features due to stagnant water were observed only at one drill point (48). This sampling point is located in a forest clearing (clearly visible as a white area in Fig. 2), in which a hunter's raised hide is installed. From the wildlife feeding around drill point 48, soil compaction through animal tread resulted in waterlogging and anaerobic conditions.

Multi-element analysis

Factor analysis

Four factors were extracted, which in sum explained 78.2% of the variance (Table 1, Online Resources 2). The number of elements contributing to the factor loading varies between 1 and 14. In factor 1, 14 elements load, which are common in given parent material. At factor 2, the two elements Ca and Ti showed the highest factor loading (≥0.86). Phosphorus, as the powerful indicator of human habitation, followed with a factor loading of 0.65. Chromium loaded negatively on factor 2 (-0.52), but positively on factor 1 (0.60). TOC (0.83), P (0.55), Pb (0.82) and As (0.74) loaded high on factor 3, which could indicate an input of waste. Factor 4 is only determined by strontium (Sr) with a factor loading of 0.76.

Cluster analysis

For the four factors five clusters could be generated. The number of samples (n) that can be assigned to a cluster decreases from cluster A (126) to cluster B (81), cluster C (65), cluster D (27) and cluster E (5).

Clusters A – C are represented in the separated northern part of the main camp as well as southeast of it (the larger part of the main camp) and northeast outside of the camp (Fig. 3A – D). Cluster D was found in the separated northern part of the main camp and outside of the camp (Fig. 3A – D). The spatial distribution of clusters A, C and D are present through all depths examined. Clusters A and B show a clear dependence on depth. Cluster B has the greatest spatial extent in the top 20 cm of the Bv. Cluster A increased at the expense of cluster B with increasing depth (Fig. 3A

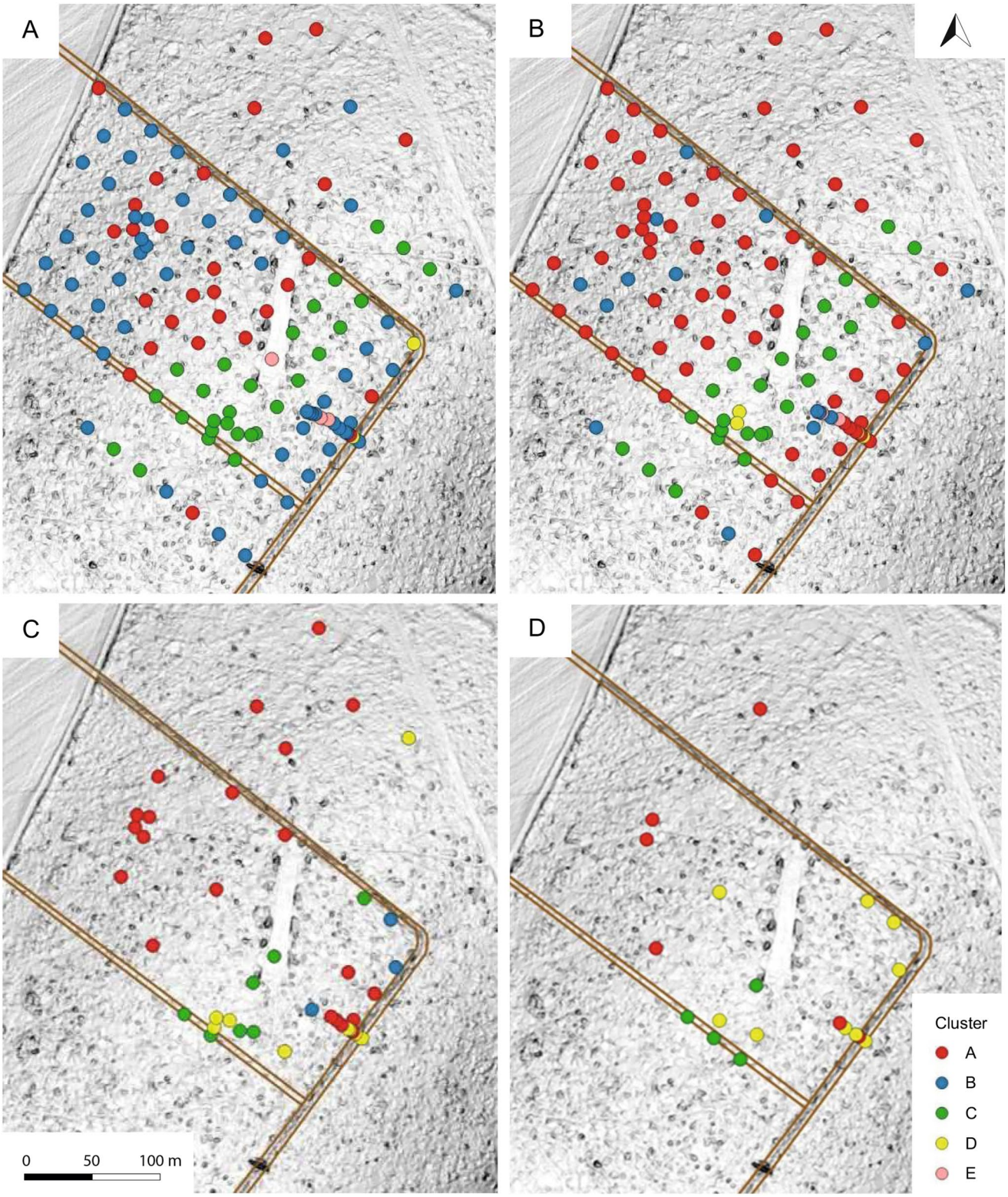

Fig. 3 Cluster distribution in the B horizons of the separated northern part of the main camp and outside the Roman fortress near Hermeskeil. (**A**) upper 20 cm of the Bv, 20–40 cm of the Bv, (**C**) 40–60 cm of the Bv, (**D**) 60–80 cm of the Bv. The decreasing number of samples with depth resulting from the thickness of the soils

– C). The spatial distribution of cluster C is limited to a broad band across the camp, and at the northeastern sampling points outside of the camp (Fig. 3A, B). Cluster D also shows a depth dependence and dominates at depths > 40 cm of the Bv. It was mainly located in the disturbed area near the camp's bank (Fig. 3C, D). Cluster E was the only one located solely in the separated part of the camp, here mainly in the *intervallum*, and it contains only samples from horizons < 40 cm of the Bv (Fig. 3A, B).

Factor values of clusters

Significant differences in values of factor 1 were found only between clusters B and C (Fig. 4A) and attributed to geological differences. Even though some of the elements (e.g. Zn, Ca, Cr, Cu) have been used as indicators for habitation effects (Ottaway and Mathews 1988; Nielsen and Kristiansen 2014), factor 1 combines elements that represent the geological setting. Local geology contributed a suite of Fe, Ba, Al, V, Co, Ni, K, Na, Li, Cu, Mg, Mn, Zn and Cr (Online Resources 2). A range of these elements was comparable with soils formed from solifluction layers of Devonian sandstones, quartzites and shale (Hauenstein et al. 2013). Based on the element contents, substrate change can be observed within the investigated area. The mean contents of elements listed above (factor 1) in our study were between those given for the Devonian sandstones, quartzites and mudstone, siltstone, and shales respectively (Online Resources 4). Cluster C shows significantly higher concentrations of the above elements and presents the mudstones, siltstone, and shales, while cluster B with its lower elemental contents indicates a different parent material (sandstone, quartzites). Clusters B, D, and E appear to be a mixture of both parent material.

Regarding factor 2 (Ca, Cr, Ti, P), clusters A, B and C differed significantly from clusters D and E (Fig. 4B). Furthermore, the latter clusters differ from each other. Enrichment of phosphorus can be observed as a result of disposing excrement, waste and organic decay (Kulkova 2022; Kanthilatha et al. 2017). Therefore, the concentration of organic materials should also indicate a high content of TOC (Deotare and Joshi 1981). However, TOC was not involved in the loading of the factor 2.

The clearest difference among the clusters resulted from factor 3. In cluster E, this factor loads significantly higher than in all other clusters (Fig. 4C). All elements from factor 3 (TOC, P, Pb, As) showed the significantly highest concentrations in cluster E. A strong association of TOC and P indicates a waste input (Woods 2003; Oonk et al. 2009a). Within cluster E, concentrations (mg kg^{-1}) of contents up to 80 and 830 were determined for TOC and P, respectively. Thus, of all the bioelements, P probably leaves the strongest and longest lasting imprint in soils from human settlement (Sjöberg and Sjoberg 1976). The fact that both carbon and lead are highly charged in factor 3 is due to the high affinity of the Pb to bond with C (Sodré et al. 2019).

The factor 4, determined solely by Sr, charges significantly more in clusters A and E than in clusters B – D (Fig. 4D). In the literature, high levels of strontium are associated with fireplaces (Wilson et al. 2008) as well as bones and domestic waste (Nielsen and Kristiansen 2014). Sr is almost as good a marker of human settlement activity as phosphorous (Ottaway and Matthews 1988). The high variation of the factor loading in cluster E compared to cluster A could indicate anthropogenic overprinting of the geologic signal.

Several studies note that chemical patterns in sediments may be highly influenced by factors related to a site's natural environment (e.g. geology, hydrology) (Oonk et al. 2009b; Wilson et al. 2006; Vyncke et al. 2011). In our study, geological differences are strongly traceable through the elemental distribution of the soils. The regular cluster distribution facilitates the assignment of the geological influence here. The processes of soil formation after deposition are negligible in our study. The soils within the study area are characterized by the two transformation processes (formation of pedogenic Fe-oxides and clay minerals) and incipient podzolization (translocation process).

Although we examined the soils along a relatively coarse grid (25 × 25 m) and sampled more densely only in small areas, it was possible to identify areas that were probably anthropogenically influenced. Cluster E stands out clearly (in some cases significantly) from the other clusters (Fig. 3B – D). We therefore interpret cluster E as an anthropogenic imprint.

Concentrations and ratios of faecal biomarkers

In a further step, we examined whether this finding can be supported by biomarker analyses and whether even the source of the waste can be identified. Four samples for biomarker analysis were selected from cluster E. Three samples from this cluster came from the *intervallum* (T08, 21–41 cm; T09, 1.5–21.5 cm; T011, 27–37 cm). One sample of this cluster was spatially isolated from the other samples and located in an area (48, 10–12 cm) surrounded by cluster C (Fig. 3). For comparison, two samples each were taken from clusters A (5, 30–50 cm; 45, 34–54 cm) and B (4, 30–50 cm; 44, 24–44 cm).

The clear delineation of cluster E from the other clusters by elemental determination was supported by biomarker analysis. Apart from the exception of the near-surface sample T09 (cluster E), concentrations of biomarkers were highest in cluster E (Online Resources 5). Coprostanol, diagnostic for omnivore faeces (Bull et al. 2002; Harrault

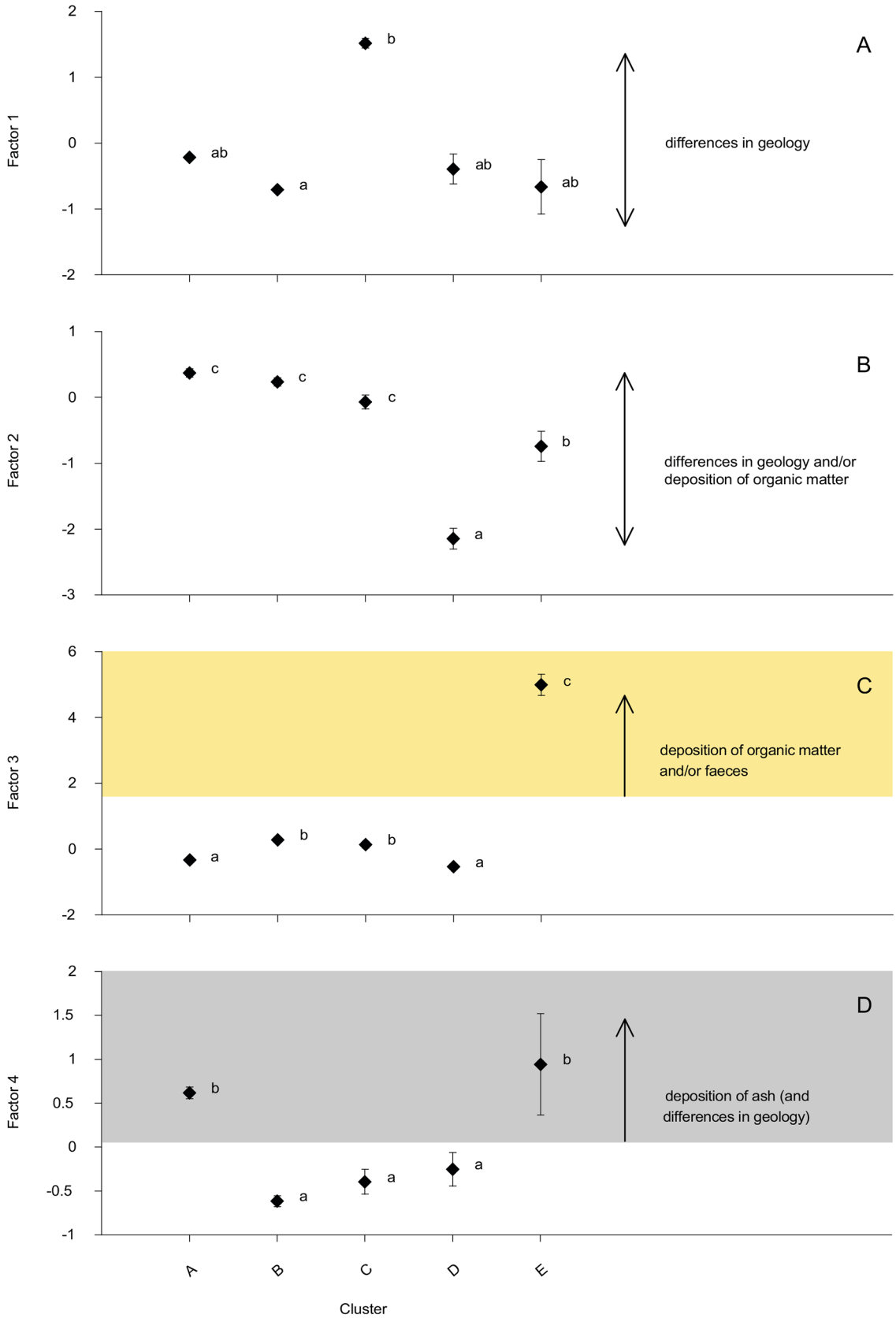

Fig. 4 Arithmetic mean of factor loadings of (**A**) factor 1, (**B**) factor 2, (**C**) factor and (**D**) factor 4 in each cluster (y-axis) of the detached northern part of the camp. The x-axis shows the cluster number (**A** to **E**). Error bars reflect standard error. Identical lowercase letters represent a homogeneous subgroup. Different lowercase letters indicate significant differences between means ($P < 0.05$)

et al. 2019), was up to 14-times higher in cluster E as in all other samples (≤30 vs. ≤ 1.7 ng g^{-1}). The precursor of coprostanol, the Δ^5-sterol cholesterol, which is the predominant sterol (cell membranes) in animals/humans, was up to three-fold higher in cluster E than in other two clusters (≤367 vs. ≤ 106 ng g^{-1}).

Concentrations of Δ^5-sterols (β-sitosterol and stigmasterol), typical of plant biomass, were significantly higher than those of animal biomass. Again, concentrations of these Δ^5-sterols were highest by far in cluster E. This also applies to cholestanol and stigmastanol, the reduction products of Δ^5-sterols formed outside the mammalian digestive tract in the environment (Baeten et al. 2012). 5β-stigmastanol, characteristic of herbivore faeces (Prost et al. 2017), was quantifiable in cluster E only at sampling site 48, but here at higher concentrations (307 ng g^{-1}) than all other samples (cluster A and B≤7.8 ng g^{-1}). The 3α-epimers of the 5β-stanols (epicoprostanol and 5β-stigmastan-3α-ol) could not be quantified in only some samples (Online Resources 5).

According to concentrations of coprostanol and 5β-stigmastanol, it is likely that cluster E was affected by faeces. However, a sole interpretation of the absolute concentrations of biomarkers is critical (Birk et al. 2022). For example, high background levels of coprostanol have also been found in soils and sediments that have not been exposed to increased deposition of faecal matter (Bethell et al. 1994; Bull et al. 2001). Therefore, concentrations of biomarkers were set in relation to their isomers, which formed in the environment (Bull et al. 2002). Ratio $R1_{Omnivore}$ (Eq. 1) and $R2_{Herbivore}$ (Eq. 2) were used as indicators for faecal input from omnivores and herbivores, respectively (Prost et al. 2017).

$$R1_{Omnivore} = \frac{coprostanol}{cholestanol} \quad (1)$$

$$R2_{Herbivore} = \frac{5\beta - stimastanol}{stigmastanol} \quad (2)$$

Since herbivores and omnivores excrete both coprostanol and 5β-stigmastanol, but in different proportions, the ratio $R3_{Herbivore/Omnivore}$ (Eq. 3) was calculated to distinguish between herbivore and omnivore faeces (Evershed and Bethell 1996).

$$\frac{R3_{Herbivore}}{Omnivore} = \frac{5\beta - stigmastanol}{coprostanol} \quad (3)$$

The samples 48, T08, T011 from cluster E had high $R1_{Omnivore}$ ratios compared to samples from clusters A and B (Fig. 5A). The $R1_{Omnivore}$ ratios from cluster E, together with high concentrations of coprostanol, indicate input of omnivore faeces. Differentiation between human or pig entry would be possible by additional analysis of bile acids (Lühe et al. 2020; Prost et al. 2017; Bull et al. 1999a), which, however, we did not investigate.

In contrast to the cross-section samples, the 5β-stigmastanol in the spatially isolated drilling point 48 (cluster E) was also quantifiable. Both high R2, R3 ratios (Fig. 5B, C) and concentrations of 5β-stigmastanol point to faecal input from herbivorous wildlife at this point, which was located at a game feeding site near a hunters' hide. The assignment of near-surface sample T05 to cluster E may be based on recent inputs of organic matter.

Interpretation of the Northern part of the main camp

The presence of cavalry over a period of several weeks in the investigated area can be excluded on the basis of multi-element and lipid analyses.

This analytical result of our study is underlined by theoretical calculations of the impact that would have to be expected during an extended stationing of cavalry units. Per horse and day, 10 to 20 kg of faeces and 5 to 10 L of urine are excreted (Bender 2000). Depending on feed, their urine may contain 0.14–1.75 mmol P l^{-1} and 2.64–11.6 mmol Ca l^{-1} (Zeyner et al. 2017). If we assume that horses were present inside the camp, we can make a rough estimate. According to(Raaflaub and Ramsey 2017) the duration of camp use in this particular case can be estimated to about three to four weeks. In 30 days, with a horse population of 500 horses and a stall area of 9 m^2 per horse, the mean input via urine is 3.9 g P and 38.6 g Ca. At an average of faecal dry matter (DM) of 184 g kg^{-1}, horse faeces contains 4.3 g $kg^{-1}{}_{DM}$ P and Ca (Lindroth et al. 2022). The estimation of element input through faeces is based on the same assumptions made for element input through urine. The estimated input (per m^2) from faeces is 160 g P and Ca.

Ca and P load high in factor 2 and differentiate clusters E and D from the other clusters. But cluster D and E occurs only on a small scale, i.e. the area is too small for the number of horses estimated in case of the stationing of cavalry. Our extrapolation is probably still overestimated, since the animals were certainly not penned all dayand there could have been fewer horses. Nevertheless, even with a coarse-mesh sampling grid, we should have found significant element accumulation in the camp's interior as a result of stationing cavalry. This is especially true for phosphorus, which remains in the soil for a long time (Sjöberg and Sjoberg 1976).

Additionally, biomarker analyses did not provide evidence for the presence of horses in the northern part of the main camp either. Typical for horse (*Equus caballus*) faeces

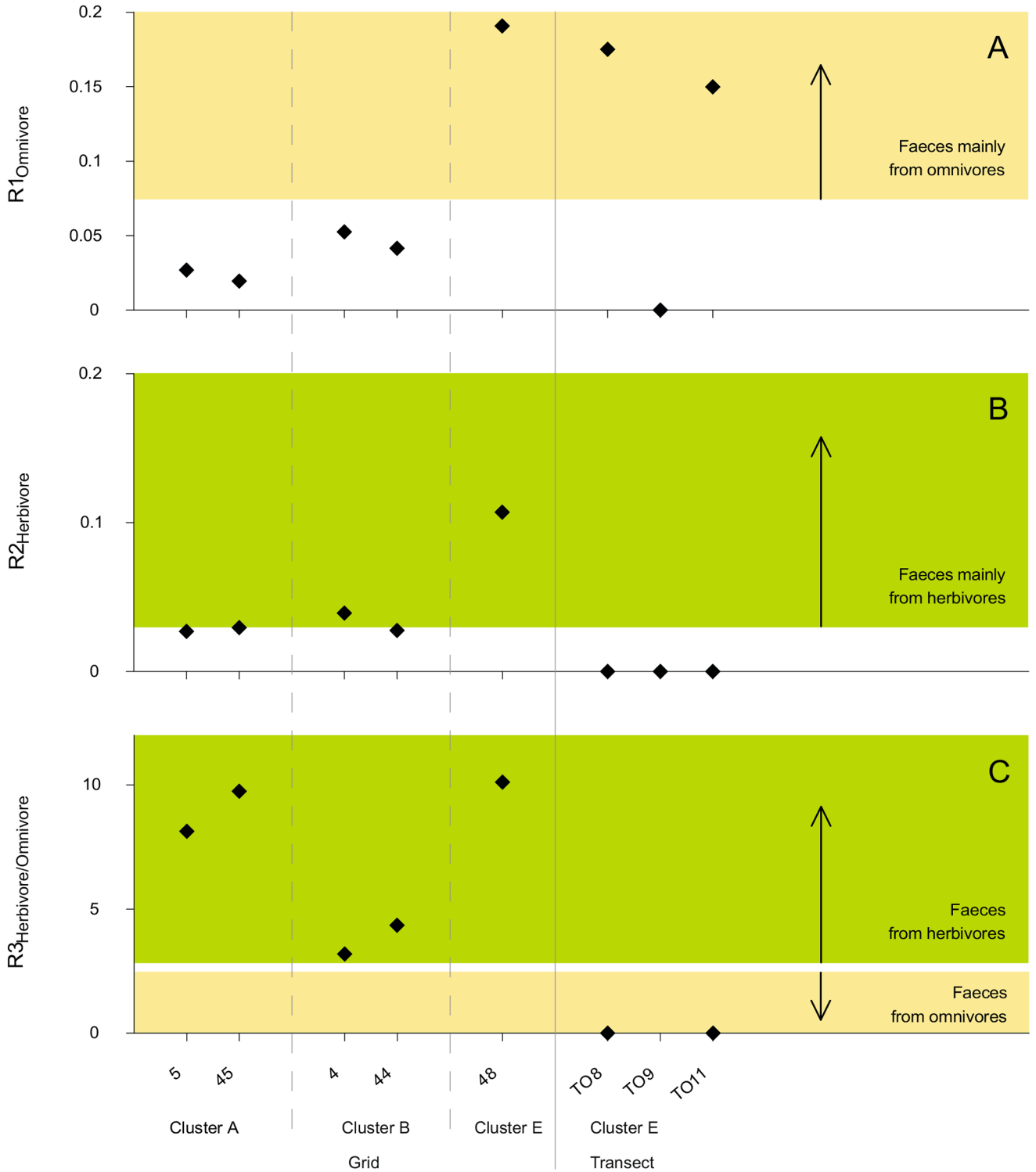

Fig. 5 Steroid ratios of the studied samples from clusters A (5, 30–50 cm; 45, 34–54 cm), B (4, 30–50 cm; 44, 24–44 cm) and E (48, 10–12 cm; intervallum: T08, 21–41 cm; T09 1.5–21 cm; T011 27–37 cm). (**A**) $R1_{Omnivore}$ (ratio of coprostanol to cholestanol, (**B**) $R2_{Herbivore}$ (ratio of 5β-stigmastanol to stigmastanol), (**C**) $R3_{Herbivore/Omnivore}$ (ratio of 5β-stigmastanol to coprostanol)

is a high abundance of 3α-epimers of 5β-stanols in relation to 3β-epimers. Typically, the ratio of epi-5β-stigmastanol/5β-stigmastanol in faeces of horses is close to one (Prost et al. 2017), and therefore much higher than in faeces of other farm animals. In our case, epi-5β-stigmastanol/5β-stigmastanol ratios were low compared to the other markers recorded and epi-5β-stigmastanol was not quantifiable in all samples (Online Resources 5).

Only samples of cluster E showed slightly higher P concentrations. In this area, faecal markers indicate a significant input from omnivores (ratio $R1_{Omnivore}$), by all probability suggesting a latrine in short-term use. The ratio $R3_{Herbivore/Omnivore}$ (5β-stigmastanol/coprostanol) in the *intervallum* samples also supports the existence of a latrine. Herbivore faeces contain significantly more 5β-stigmastanol than coprostanol, and pig faeces also contains considerable amounts of 5β-stigmastanol (Prost et al. 2018). No 5β-stigmastanol was found in samples T08 and T11 (intervallum). Only human (and other primates) show a strong dominance of coprostanol in their faeces (Prost et al. 2018). Additional bile acid analysis could be used to confirm is the existence of a latrine. Individual patterns of bile acids are the result of evolutionary variation, and to a lesser degree diet (Hagey et al. 2010). Faeces of humans and pigs can be differentiated with bile acids with a high degree of certainty because the dominant secondary bile acid in pig faeces is hydrodeoxycholic acid, which is not present in human (Elhmmali et al. 1997).

The location of cluster E samples in the area of the *intervallum*– the unpleasant odours emanating from latrines generally favoured a location at some distance from the soldier's quarters– would in fact correspond well with that of latrines known from other Roman camps with either a temporary or more permanent use (Johnson 1987; Reddé et al. 2006). In their simplest form, these represent elongated pits with wooden seating and an eventual roof or shed for weather protection, known e.g. from the Imperial-period fortresses at Künzing and Usk (Schönberger 1975; Manning 1981). In contrast, it can be ruled out that the faecal marker signal may have been caused by omnivore waste e.g. in mudbrick because the adjacent bank was evidently constructed from turves (Hornung 2024) and the signal did not appear in other areas of the *intervallum*. Even though the keeping of omnivores, and pigs in particular, inside a Roman camp cannot be ruled out with any certainty (Prost et al. 2017) it is rendered very unlikely by the temporary character of the Hermeskeil fortress. Army provisioning during active campaigns, at least in the Caesarian period, can be considered a purely situative measure since a lack of supply infrastructure is known from both historical and archaeological sources (Labisch 1975; Hornung 2024). With respect to the actual function of the main camp's northern part as a key question of this study, it is very likely that the reason behind the building of an internal fortification does not lie in a separate stationing of cavalry. The results of soil analyses, therefore, speak in favour of a secondary reduction of the main camp's surface and its connection with two successive Roman campaigns. Both periods of use must have been chronologically close because they are not in any way reflected in the archaeological finds from Hermeskeil. A similar re-use of military sites is very common in Roman times (Jones 2011) and in our case even well in line with historical sources, which inform us of two Roman campaigns in the area in 53 and 51 BC, both commanded by Caesar's legate Titus Labienus (Hornung 2019).

Conclusion

In contrast to other studies, we identified only a few site-specific elements as indicators of human influence (P, C, Sr). Our data showed that minor geological differences and recent inputs affected element and biomarker concentrations more than the Roman military use at most sampled points. Based on our data, it seems, therefore, unlikely that cavalry could have been stationed in the systematically examined northern part of the Hermeskeil main camp over a period of several weeks. The combination of multi-elemental and biomarker analysis will open new frontiers in our understanding of the human past. It was possible to identify latrines in the area of the *intervallum*. This indicated that the separated northern part of the main camp probably saw a regular use for the stationing of infantry, but not allied cavalry, and was used only during the first of two successive campaigns. The building of an internal fortification, therefore, marks a reduction of the camp's surface in a second phase of occupation.

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Declarations

Competing interests The authors declare no competing interests.

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