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Multi-element soil prospection aiding geophysical and archaeological survey on an archaeological site in suburban Sagalassos (SW-Turkey)

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A B S T R A C T

In order to take full advantage of the archaeological information contained within buried archaeological sites, it is important to apply an integrative approach combining complementary prospection methods. In this study, geochemical prospection data are combined with archaeological and geophysical survey results on an unexcavated site in suburban Sagalassos (SW-Turkey), with the aim of obtaining better insights into the structural shapes and past functionalities of the area. Spatial and multivariate statistical analyses of the chemical data reveal anomalies of K, P and Zn on a location where archaeological and geophysical results suggest the presence of ceramic producing kilns. These elemental enrichments are thought to result from burning wood or dung as fuel for the detected kilns. In addition, local anomalies of Co, Cr, Fe, Mg, Mn and Ni were found to reflect the working and storage of ophiolitic clays, employed as a raw material for ceramic production. Radiocarbon dating of charcoal in a 2.5 m deep drill core in this zone provides ages between AD 120 and 350 at depths of 50 and 60 cm. Al, As, Ba, Ca, Na, Sr, Ti and Pb are considered geogenic elements in this study. The present study supports the theory that geochemical prospection holds potential as a surveying technique, as it was found that chemical data facilitate the interpretation of structures detected by geophysical and archaeological methods, thereby creating an extra dimension to the interpretation of survey data. The results further argue in favour of using strong-acid extractions and the consideration of a large suite of elements when applying chemical soil survey as an archaeological prospection technique, and highlight the importance of considering site lithology. Multivariate statistics proved to be invaluable in distinguishing anthropogenic from lithological soil patterns.

1. Introduction

It has been widely recognised that surveying at archaeological sites provides a robust, cost-effective methodological tool to study the buried archaeological record (Banning, 2002; Sullivan et al., 2007). At the present day, a large variety of survey techniques exist, providing information on the delineation, characteristics and functionality of buried archaeological sites. While these methods may generate useful information on one or a few aspects of the buried record when applied as a stand-alone technique, recent studies on archaeological survey strategies have stressed the importance of integrating different methods in order to obtain a more generalised and objective understanding of the complex history of buried sites (Barba, 1994; James, 1999; Clay, 2001; Keay et al., 2009). In this study a multi-analytical approach, combining intensive archaeological, magnetic and geochemical prospection, including sediment coring, was chosen to achieve comprehensive insights into the dimensionality and functionality of a covered site in the territory of ancient Sagalassos (SW-Turkey).

2. Background

Over the last century, the combination of geophysical and archaeological prospection techniques has become standard practise (Banning, 2002; Gaffney, 2008). Magnetic methods especially have proved highly valuable in detecting and mapping buried archaeological structures and artefacts, as most man-made features have magnetic properties that are distinctly different from the soil in which they are hosted (Aitken, 1974; Aspinall et al., 2008;

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Stampolidis and Tsokas, 2012). Conversely, multi-element soil analyses have only been integrated rarely into archaeological survey programmes (Oonk et al., 2009a). Nevertheless, there is a long history of analysing archaeological soils at excavated archaeological sites. Based on the premise that multi-element signatures may provide information on an extensive range of ancient human activities, numerous studies have reported on a wide variety of elemental enrichments and depletions associated with ancient anthropogenic activities (Bintliff et al., 1990; Barba, 1994; Linderholm and Lundberg, 1994; Entwistle and Abrahams, 1997; Degryse et al., 2003a; Wells, 2004; Middleton, 2004; Cook et al., 2005; Oonk et al., 2009b; Hutson et al., 2009; Abrahams et al., 2010; Davidson et al., 2010; Vyncke et al., 2011). More recently, efforts were made to review and validate the method. Hereby, large numbers of soils from known archaeological contexts were analysed and compared (Entwistle et al., 2000; Haslam and Tibbett, 2004; Wilson et al., 2005, 2009; Oonk et al., 2009a; Dore and López Varela, 2010), sometimes within contrasting geological and environmental settings (Luzzadder-Beach et al., 2011). The outcome of these projects has revealed that ancient soil signatures are highly site-specific and often difficult to interpret (Wilson et al., 2009; López Varela and Dore, 2010). This can be attributed to the combined effect of natural variations in background geology, post depositional soil processes and large concentration ranges of archaeological input material, all factors for which deriving a quantitative estimate is challenging (Wilson et al., 2008; Oonk et al., 2009b). It is important to take these pitfalls and restrictions into consideration when applying soil chemistry as a survey technique (James, 1999; Walkington, 2010).

3. Study area

Çatal Oluk, the site under study in this paper, is located 1 km south of ancient Sagalassos. Sagalassos was a Hellenistic to Byzantine city located in the Taurus Mountains in southwest Turkey, approximately 100 km north of Antalya. The site was discovered during a large-scale suburban archaeological survey in 2002 (Vanhaverbeke and Waelkens, 2003). Based on the distribution and functional composition of the surface sherds and the presence of a monumental tomb, it was proposed that the area was the former location of an ancient villa site or farming estate (Waelkens, 2006). Today, the site is composed of fallow farmland, but the area has been cultivated and ploughed during the past century. Several terraces composed of limestone blocks are present on the surface, some of which may date back to ancient times. Çatal Oluk comprises an area of 40 ha that is located on a gently south-dipping (5–6°) slope, situated on the watershed of two north-south oriented valley systems. Located at an altitude of 1280 m in a subhumid to humid precipitation regime, the climate can be classified as Oro-Mediterranean (Paulissen et al., 1993). The soil is composed of colluvium rich in limestone fragments, weakening the soil structure and hence reducing farming possibilities. From a geological point of view, Çatal Oluk is underlain by siliciclastic flysch deposits, formed during the infill of a Miocene foreland basin in front of the so-called "Lycean Nappe complex" (Muchez et al., 2008). This nappe complex, outcropping in the vicinity of the study area, comprises limestone and ophiolitic mélange units (Fig. 1). Numerous volcanic tuff fragments were found in the southern and western part of the site, resulting from

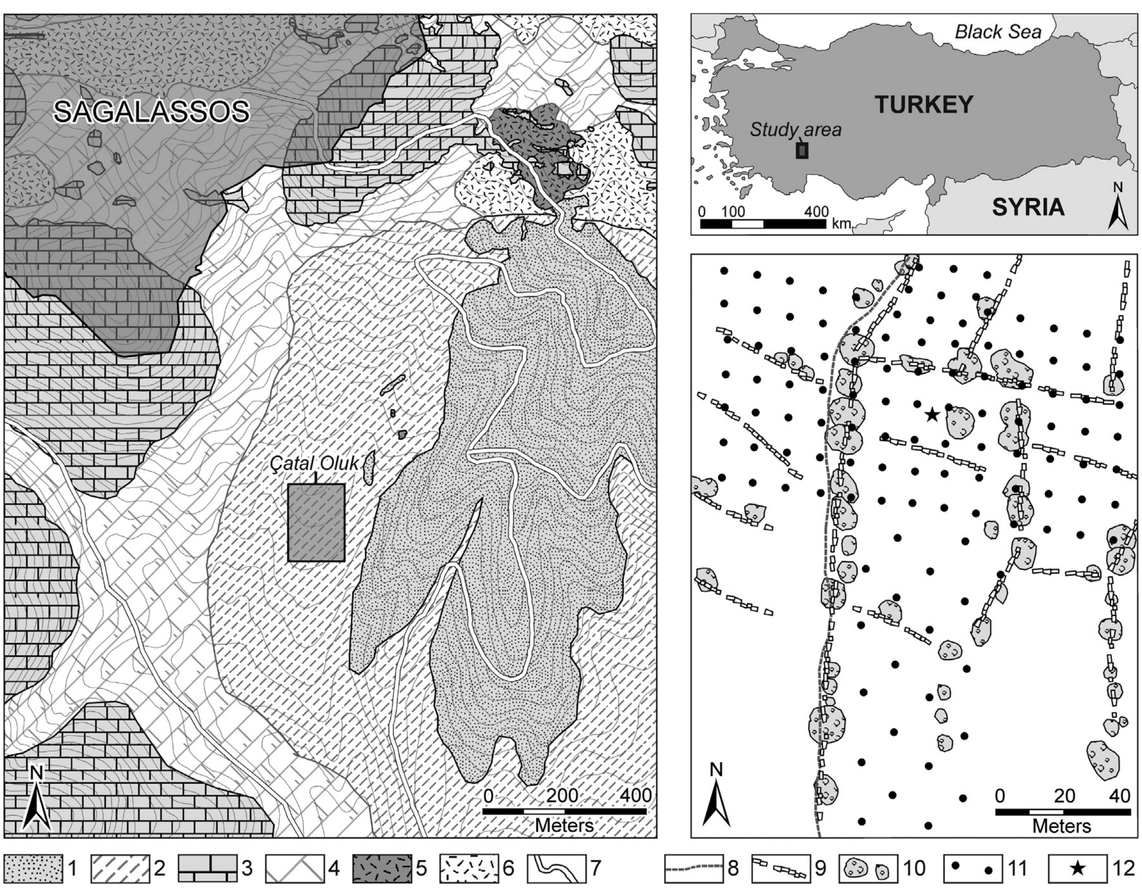

Fig. 1. Location of the study area and map of the sample grid. 1. Flysch outcrop. 2. Soil on flysch bedrock. 3. Limestone outcrop. 4. Soil on limestone bedrock. 5. Ophiolite outcrop. 6. Soil on ophiolitic bedrock. 7. Road. 8. Trail. 9. Agricultural terrace. 10. Tree. 11. Sampling point. 12. Core.

Quaternary eruptions of the Gölçuk volcano, located 5 km north of Sagalassos (Alıcı et al., 1998).

4. Material and methods

4.1. Intensive archaeological survey

In order to get a more detailed understanding of the character and function of the site discovered during the suburban survey, the site was intensively re-surveyed in 2010. As this survey aimed to also detect faint traces of human activity and not just settlement remains, a method was developed to identify unobtrusive surface scatters larger than 10 m in diameter. Survey personnel were positioned at 10 m intervals and each person surveyed successive transects of 25 m long and 1 m wide, with orientations in accordance with field boundaries. GPS-points were recorded on each transect, and all man-made artefacts were collected, with the exception of plastic and obviously modern metal and glass. After collection, all finds were counted and grouped according to age, function and weathering condition Inline Supplementary Table S1.

Inline Supplementary Table S1 can be found online at http://dx.doi.org/10.1016/j.jas.2013.02.033.

4.2. Geophysical prospection

Based on the rough field conditions and the expected nature of archaeological features, a magnetometer survey was considered the most suitable technique for geophysical prospection in this case. Magnetic measurements were carried out using a Geometrics G858 Caesium magnetometer in pseudo-gradient mode (nT/m). This setup amplifies weaker magnetic anomalies of small structures at shallow depths, thereby suppressing background noise of long-wave anomalies caused by geological background (Sharma, 1997). Top and bottom sensors were fixed respectively 100 and 30 cm above the ground. The magnetometer attained a resolution of 0.1–0.2 nT/m in measuring total magnetic field density with an acquisition rate of 5 Hz along 0.5 m spaced transects. Readings were taken at 15 cm intervals along east-west oriented survey lines. An upward continuation filter, minimising the effects of shorter-wavelength noise associated with shallow surface layers, was applied to improve recognition of human made features (Kearey et al., 2002). Measured values were interpolated in both directions to a sample interval of 0.25 m using a cubic spline approximation to the sinc function (Scollar et al., 1990).

4.3. Topsoil sampling, coring and dating

A total of 103 soil samples were taken at 15 cm depth in a regular grid with sample cell sizes of 10 × 10 m and 20 × 20 m in areas with higher and lower ceramic sherd concentrations, respectively. To explore the soil stratigraphy at the studied site, a core with a depth of 2.5 m and a width of 7 cm was drilled using a Ramguts corer at a location containing a large surface scatter of artefacts (Fig. 1). Charcoal fragments found in two samples allowed for radiocarbon dating. Radiocarbon dates are obtained from Beta Analytic (BETA). ^{14}C-ages were acquired with accelerator mass spectrometry (AMS) after acid-alkali pre-treatment. The conventional radiocarbon dates displayed in Table 1 are corrected for isotopic fractionation using δ^{13}C-values. Calendar calibrated ages are calculated according to the INTCAL04 database (Reimer et al., 2004).

4.4. Multi-element analysis

Soil samples were oven-dried (105 °C) and sieved, after which subsamples (0.5 g) of the 63 μm-fraction were digested in 10 ml Aqua Regia (3:1 HCl 37%: HNO_3 65%) at 140 °C for 1 h and evaporated at 200 °C until almost dry. The residue was redissolved in 2.5 M HNO_3. After filtering and dilution to 50 ml, solutions were analysed with ICP-OES. A Varian 720-ES instrument supplied with double-pass glass cyclonic spray chamber, concentric glass Sea-Spray nebulizer and “extended high solids” torch was used. An ionisation buffer (1% CsNO3 in 4% HNO_3), intended to eliminate ionisation effects, was added. Concentrations of 19 elements (Al, As, Ba, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, Sr, Ti, V, and Zn) were determined from one single analysis run. Calibration solutions were prepared from certified Plasma HIQU single element solutions (CHEM-LAB, Belgium). Ultra pure water (>18 MΩ/cm^3) and analytical reagent grade acids were used in this work. Two certified reference soil materials (BCR-143R and QCM-31) were also digested and analysed. Precision was calculated for all elements by repeated measurements of independent standard solutions and was determined to vary between 2 and 9.5% RSD, with highest values being for Na and Ti Inline Supplementary Table S2.

Inline Supplementary Table S2 can be found online at http://dx.doi.org/10.1016/j.jas.2013.02.033.

Table 1
AMS ^{14}C dates of drill core samples.

Sample	Depth (cm)[a]	Laboratory code	δ^{13}C (‰ PDB)	Conventional ^{14}C age (BP)	Cal (2σ) age[b]
SA10KD065	50	Beta-296427	−24.2	1790 ± 40	AD 130–340
SA10KD066	60	Beta-296428	−22	1830 ± 30	AD 120–250

[a] Relative to surface level.
[b] 95% probability.

4.5. Data analysis

A non-parametric Wilcoxon rank-sum test was carried out to statistically establish which elements of the dataset are significantly enriched when compared to regional lithological baseline values (see Section 5.4.1). Element concentration values were transformed prior to multivariate analysis using a centred log ratio transformation, to “open” the dataset and reduce the effect of individual outliers (Buccianti, 2006). Data were statistically grouped using Ward’s hierarchical clustering based on Euclidean distances. A bivariate plot of the first two principal component scores (based on the correlation matrix) was overlain by a vector plot containing variable loadings. This representation combines information on which elements differentiate between sample clusters with information on the relationship between individual variables. Because Ca contains major individual outliers, and was found to severely influence results from principal component analysis (PCA), it was decided to exclude this element from the PCA. All statistical analyses were performed using R software (R core Team, 2012), while spatial plotting was carried out with ArcMap 10.

5. Results

5.1. Archaeological survey

Archaeological dating of the pottery sherds present at the surface of the site suggests a Classical–Hellenistic to Roman Imperial/Early Byzantine age (Waelkens et al., 2012). From a functional point of view, the sherds are composed of cooking wares, table wares and storage vessels, with a remarkable domination of table wares. Spatial distribution of the collected sherds (Fig. 2) demonstrates that there is no clear patterning, although concentrations tend to be higher in the north-eastern and south-western part of Çatal Oluk. Next to sherds, large numbers of ceramic tiles and bricks, dated to

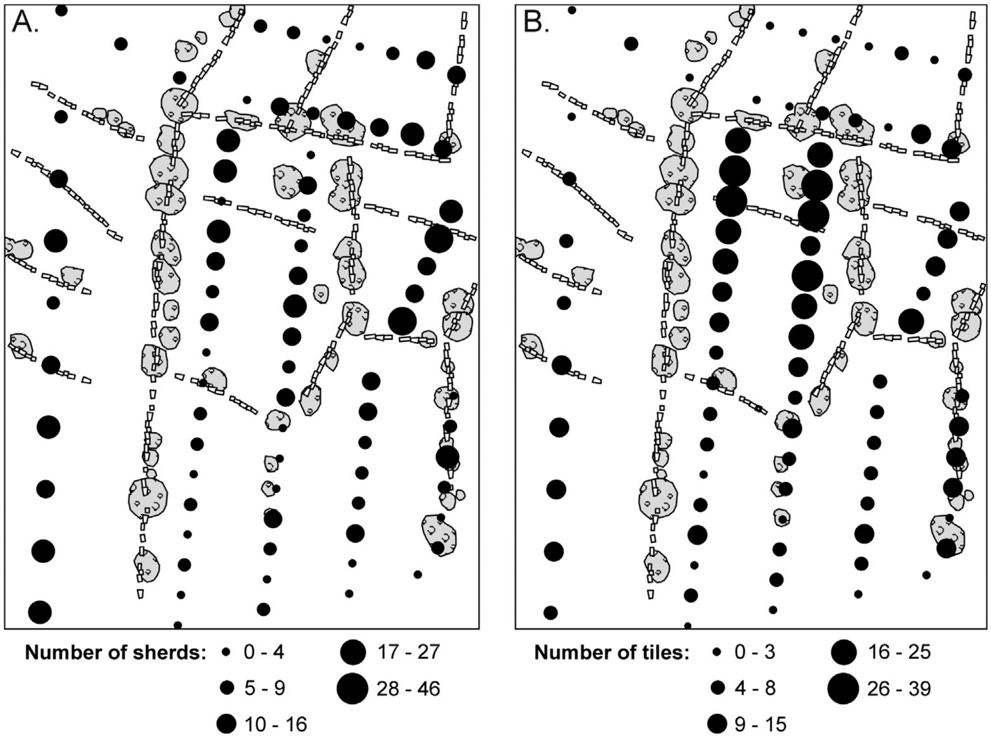

Fig. 2. Bubble plots of the total number of ceramic sherds (A) and tiles (B) found in each transect, collected during the archaeological survey. Transects are 25 m long and 1 m wide.

the Roman Imperial/Early Byzantine period, are present at the site. The tiles display a clear spatial segregation, with highest quantities located in the north-central part of the site. The amount of tiles decreases gradually towards the south, following the gently south-dipping topography.

5.2. Geophysical prospection

The magnetometer survey detected various disturbances in the study area. Solely based on the geophysical data, these disturbances can be divided into three categories. A first category of reflections corresponds with modern agricultural land use (Fig. 3A,1). It is composed of anomalies generated by modern field boundaries and terrace walls. A second category comprises strong reflections with a circular shape in the north-central part of the study area (Fig. 3A,2, Fig. 3B). Magnetic responses of these disturbances are high, with gradients up to 135 nT/m, and the features are surrounded by a halo of negative values. The third category is composed of narrow linear and semi-linear anomalies with varying orientations (Fig. 3A,3).

5.3. Drill core stratigraphy, ceramic content and radiocarbon dating

A sediment core was drilled at the location marked by a star in Fig. 1. The core consists of 5 stratigraphic layers, subdivided into three different categories (Fig. 4). Category 1 contains a brown silt layer, with moderate amounts of limestone, flysch and volcanic tuff fragments. Category 2 comprises a strongly disturbed soil matrix with a high stoniness, consisting mainly of weathered limestone fragments up to 10 cm in size. The material in category 3 is similar to category 1, but is coarser and contains higher amounts of limestone clasts with respect to flysch and tuff fragments. No soil development could be observed in the upper layer of the core. In general, the material in the core is interpreted as colluvium. Numerous ceramic fragments ($\leq$5 cm) are present in the upper 40 cm of the core. The fragments become smaller and sparser with depth. Archaeological dating of ceramics in the core suggests Roman to Early Byzantine ages. Two samples contained sufficient amounts of charcoal material for AMS radiocarbon dating (Table 1). Dates of the samples display an orderly

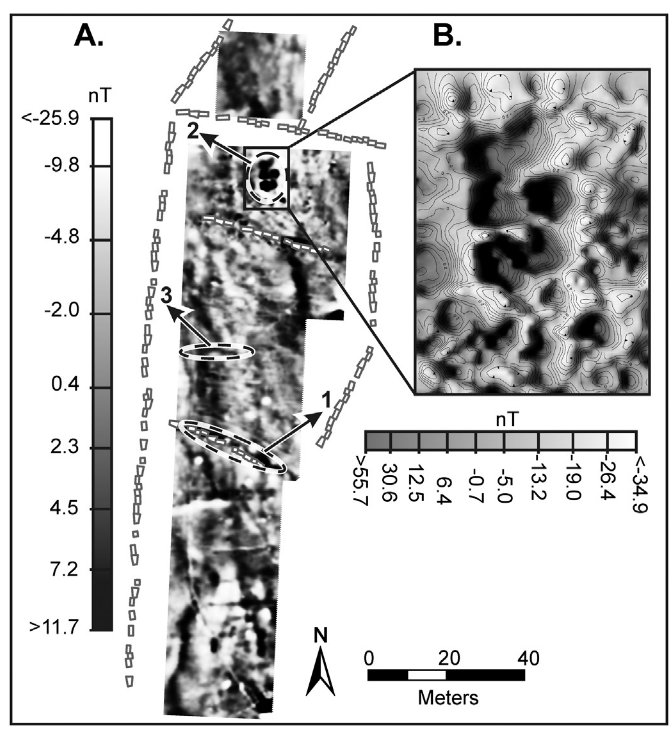

Fig. 3. A. Magnetic gradiometer map after applying an upward continuation filter. 1. Example of an anomaly due to contemporary terraces. 2. Strong circular reflections. 3. Example of a linear disturbance. B. Hill shaded image of the area containing circular anomalies.

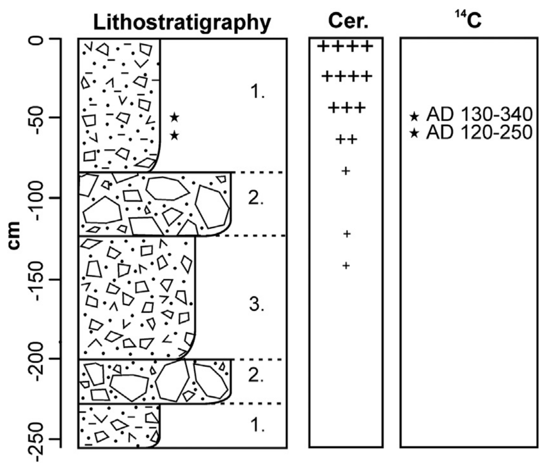

Fig. 4. Lithostratigraphic description, relative ceramic content (Cer.) and depth of dated charcoal fragments (^{14}C) for the drill core. 1. Brown silt layer with moderate amounts of limestone, flysch and tuff fragments. 2. Coarse material with high amounts of large limestone clasts. 3. Sandy layer with high limestone content and moderate amounts of flysch and tuff fragments.

relationship with depth, with ages of AD 130–340 (50 cm) and AD 120–250 (60 cm).

5.4. Geochemical survey

5.4.1. Comparison with background values

Elemental concentration levels are available for the weathering products of the three lithological units outcropping in the vicinity of the site (Table 2). Background values are based on 15 to 20 samples of weathering material of each lithology, collected within the borders of the territory of Sagalassos, dissolved and measured using an identical procedure as the soil samples of Çatal Oluk (D'Haen et al., 2012). It has to be noted that the complex polyphase tectonic history of this region has created intensely disturbed geological units (Poisson et al., 1984), which bring about relatively large concentration ranges for each lithology.

A similar database containing elemental concentration ranges for the Gölçuk tuffs is not available, but careful comparison with published literature information suggests that the tuff deposits are enriched in Ba, K, Na, Sr and Pb when compared to other lithologies present in the territory (Alıcı et al., 1998; Muchez et al., 2008). Resulting p-values from a Wilcoxon rank-sum test indicate that soils at Çatal Oluk are significantly enriched in Al, Ba, Cu, K, P, Pb, Ti and Zn with respect to median concentrations in weathering products of limestone, flysch and ophiolitic mélange units (Table 3). Even so, the interquartile ranges of Çatal Oluk soils and background lithologies display a fairly large overlap for most of these elements (Table 2) Inline Supplementary Table S3.

Inline Supplementary Table S3 can be found online at http://dx.doi.org/10.1016/j.jas.2013.02.033.

5.4.2. Superficial trends: cluster distribution

In order to detect similar sets of samples, a hierarchical clustering was performed, using all 19 variables in the transformed dataset. Four clusters were selected based on the cluster dendrogram and are spatially mapped in Fig. 5. For every element, boxplots containing median, 25% quartiles and 75% quartiles have been calculated for each of the four clusters (Fig. 6). These boxplots show that clusters 1–2 and clusters 3–4 are chemically more similar. This is confirmed by the average Euclidean distances between the different clusters (Table 4).

Clusters 1 and 2 contain higher concentrations of Co, Cr, Fe, Mg, Mn and Ni when compared to clusters 3 and 4. On the other hand Al, As, Ba, Na and Pb are in greater concentrations in clusters 3 and 4 than in clusters 1 and 2. Overall, cluster 3 is distinguished by its significantly elevated concentrations of Ca and Sr. Cluster 4 contains the highest median concentrations for Al, As, Ba, Pb and Ti. Notable are the high phosphorous values of cluster 2. With a median concentration of over 1880 mg/kg, this cluster contains P values which are almost twice as high as the other clusters. Cluster 2 also contains the highest median values for Co, Cr, K, Mg, Ni and

Table 2
Basic statistics of the soils at Çatal Oluk and weathering products of major lithological units surrounding the site. Analytical procedure was identical for all samples.

		Al (g/kg)	As (mg/kg)	Ba (mg/kg)	Ca (g/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (g/kg)	K (g/kg)	Mg (g/kg)
Çatal Oluk soil	Q1[a]	26.5	12.43	298.9	5.1	7.3	17.4	44.1	15.0	2.09	3.2
	Median	36.3	19.66	459.7	10.5	17.6	48.7	69.8	31.5	3.86	8.5
	Q3[a]	62.4	29.25	1548.8	28.3	22.1	65.9	91.6	36.4	4.78	11.6
Flysch	Q1	14.1	3.50	68.4	65.1	16.2	82.4	37.1	22.4	1.98	14.2
	Median	16.5	4.70	75.4	68.5	19.8	94.5	43.7	25.4	2.09	18.8
	Q3	19.4	5.85	76.9	75.7	23.1	110.7	52.9	30.6	2.31	36.4
Limestone	Q1	16.7	–	134.5	10.4	19.0	40.3	33.3	27.4	2.17	4.2
	Median	20.8	–	182.5	13.7	20.0	52.0	42.5	34.0	3.17	6.3
	Q3	26.4	–	240.8	23.1	23.0	68.5	56.5	37.3	3.58	7.5
Ophiolitic Mélange	Q1	5.2	–	15.0	6.1	69.8	180.5	21.3	37.3	0.31	50.6
	Median	7.1	–	25.5	17.6	108.0	235.0	28.0	42.3	0.53	120.3
	Q3	9.0	–	41.3	59.9	161.8	314.3	37.3	54.9	0.91	165.4

		Mn (g/kg)	Na (g/kg)	Ni (mg/kg)	P (mg/kg)	Pb (mg/kg)	Sr (mg/kg)	Ti (mg/kg)	V (mg/kg)	Zn (mg/kg)
Çatal Oluk soil	Q1[a]	0.43	0.16	30.5	520.0	46.6	40.8	602.7	29.2	54.7
	Median	0.96	0.31	93.1	1184.2	69.1	57.5	964.5	60.9	91.7
	Q3[a]	1.32	0.62	134.4	2356.8	99.4	95.6	1469.8	70.6	114.8
Flysch	Q1	0.50	0.28	107.4	464.7	6.7	99.9	23.8	45.3	67.1
	Median	0.69	0.35	123.8	593.3	10.2	106.4	74.0	49.4	71.2
	Q3	0.79	0.36	153.1	782.3	12.5	116.4	910.9	57.9	79.9
Limestone	Q1	1.00	0.25	66.5	552.0	20.5	21.0	20.8	42.5	66.3
	Median	1.14	0.30	75.5	623.5	28.0	24.5	42.5	60.5	79.0
	Q3	1.34	0.33	107.3	811.3	34.3	28.8	100.3	68.8	89.3
Ophiolitic Mélange	Q1	0.85	0.28	703.3	54.5	7.0	12.3	27.3	18.0	33.5
	Median	0.94	0.37	1556.5	106.5	8.0	25.0	52.5	22.0	51.5
	Q3	1.23	0.41	1795.3	131.5	10.0	34.0	111.5	27.5	62.8

[a] Q1 = 25% Quartile, Q3 = 75% Quartile.

Table 3
Wilcoxon rank-sum *p*-values for background comparison.

	Al	As	Ba	Ca	Co	Cr	Cu	Fe	K	Mg
Çatal Oluk – Flysch	**8.3E-12**	**3.1E-09**	**8.6E-05**	1.00	0.98	1.00	**6.5E-11**	**1.7E-03**	**1.6E-04**	1.00
Çatal Oluk – Ophiolitic Mélange	**1.7E-11**	–	**7.5E-12**	0.95	1.00	1.00	**4.2E-06**	1.00	**7.5E-12**	1.00
Çatal Oluk – Limestone	**2.8E-17**	–	**1.3E-17**	1.00	1.00	0.89	**1.0E-12**	0.98	**5.7E-08**	**3.4E-06**

	Mn	Na	Ni	P	Pb	Sr	Ti	V	Zn
Çatal Oluk – Flysch	**6.0E-07**	0.71	1.00	**9.9E-11**	**7.5E-12**	1.00	**1.8E-04**	**4.7E-04**	**1.9E-09**
Çatal Oluk – Ophiolitic Mélange	0.74	0.96	1.00	**7.9E-12**	**7.5E-12**	**5.6E-08**	**7.5E-12**	**3.2E-10**	**3.0E-09**
Çatal Oluk – Limestone	1.00	0.32	0.06	**2.2E-09**	**8.8E-18**	**1.4E-16**	**1.4E-18**	0.43	**1.1E-06**

H0 = the soils at Catal Oluk are not significantly enriched when compared to a background lithology. Bold *p*-values indicate significance at the 0.05 level.

Zn, and some outliers for Cu. Fig. 5 shows that several clusters are not only statistically related, but are also spatially correlated. Cluster 1 has a spatial focus in the east and the north of the study area, while samples belonging to cluster 2 concentrate in the north-central area. Clusters 3 and 4 are less clearly distinguishable in space, but both clusters are restricted to the western and southern parts of Çatal Oluk.

5.4.3. Compositional variation: principal component analysis (PCA)

The PCA scores in Fig. 7 reveal that the first principal component distinguishes clusters 1 and 2 from 3 to 4, with positive component scores for clusters 1 and 2 and negative scores for 3 and 4. The first principal component accounts for 60.2% of the variance in the dataset. The second principal component, responsible for 14% of the variance, differentiates cluster 1 from cluster 2, with positive scores for cluster 1 and negative scores for cluster 2. The distinction between clusters 3 and 4 based on this second principal component is less obvious, although the scores of cluster 3 for the second component are slightly more negative than cluster 4. It can be deduced from variable loadings that As, Al, Ba, Na, Pb, Sr, and Ti contribute negatively to the first component, corresponding with clusters 3 and 4. V, Fe, Mn, Cr, Co, Ni, Mg, K, Zn and P have positive loadings on the first principal component and visually overlap with the scores of clusters 1 and 2 in Fig. 7. Of all the elements analysed, only Cu contributes little to the first two components. When focussing on the first two data clusters, cluster 1 is characterised by high variable loadings for V, Fe, Mn, Cr, Co, Ni and Mg, while cluster 2 can be distinguished by large contributions of Mg, P, K and Zn (Fig. 7).

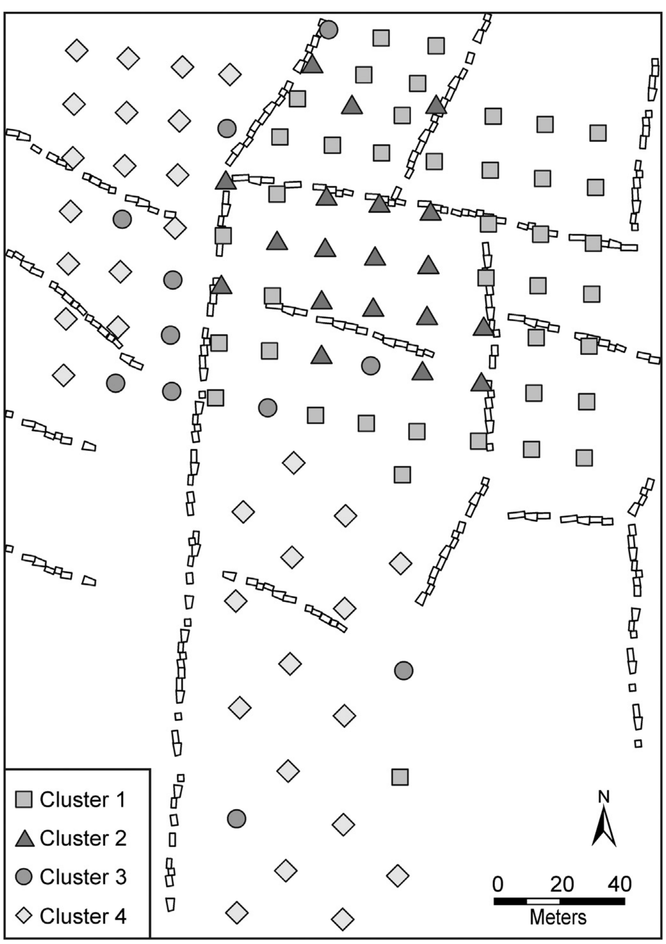

Fig. 5. Spatial cluster distribution. Clusters were calculated on the centred log ratio-transformed dataset using Ward's hierarchical clustering based on Euclidian distances.

6. Integrated interpretation

The circular shape and large magnitude of the magnetic anomalies in the north-central part of the study area suggests that they are caused by the thermoremanent magnetisation of kilns or layers of burnt clay (Aspinall et al., 2008). This circular layout fits well with the typology of excavated Roman kilns in the Sagalassos territory (Mušič et al., 2008). The archaeological survey reveals large numbers of ceramic tiles and bricks in the same area (Fig. 2); together, these results strongly suggest the presence of tile-producing kilns on this location. While no distinct anthropogenic layers could be visually observed in the drill core, the high Roman to Byzantine ceramic content in the upper 80 cm of the core indicates ancient human disturbance. Radiocarbon dates of charcoal between 50 and 60 cm present ages between AD 120 and 350, confirming that the material in this layer is associated with a time period during the site occupation. As for the chemical data, Fig. 5 shows that cluster 2 has a spatial focus in the same area where geophysical and archaeological data suggest buried kilns. This cluster is characterised by high concentrations and correlations of K, P and Zn, all elements that are found to be significantly enriched at Çatal Oluk when compared to background values. K, P and Zn are frequently cited as indicators of ancient human activity (Oonk et al., 2009a). Phosphorous can enter the soil system by a variety of human processes, such as the processing, burning or storage of organic material (e.g., food storage, wood burning), and organic waste disposal (e.g., faeces) (Schlezinger and Howes, 2000; Holliday and Gartner, 2007). Enrichments of K are mainly found in association with areas of burning, rich in organic ashes (Middleton, 2004; Oonk et al., 2009a). Anomalies of Zn can point to the presence of manure or faeces, although they also have been associated with other activities (Davidson et al., 2007; Wilson et al., 2008; Oonk et al., 2009c). Given the association with kilns in this case, the enrichments most probably result from the burning of fuel for the kilns (Pierce et al., 1998). Since Zn also is anomalous, it is plausible that next to wood, also dung may have been used as a fuel, which

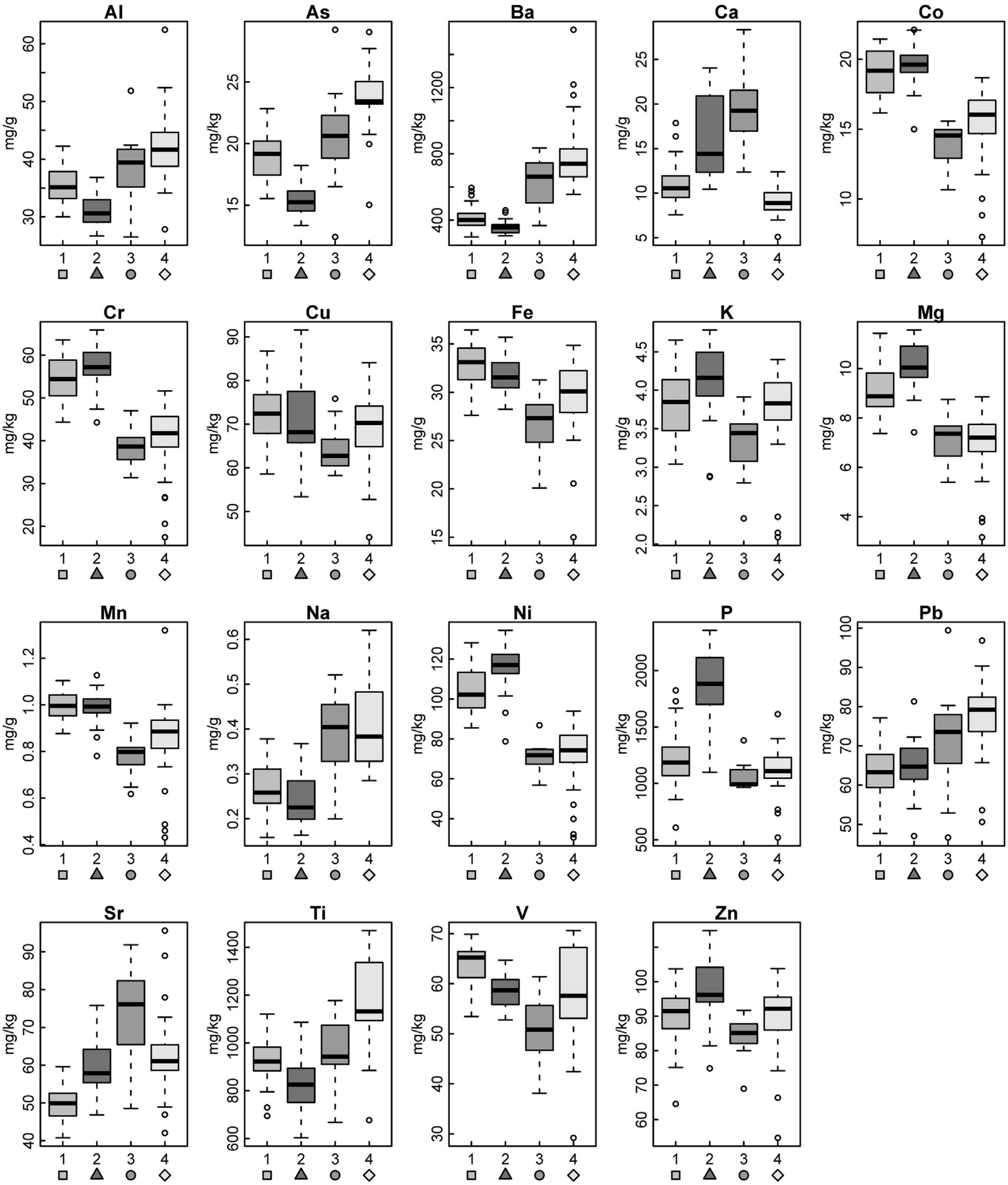

Fig. 6. Medians and quartiles of each of the four clusters. Data are displayed as individual points when values are outside the range defined by [Q1 − 1.5*IQR, Q3 + 1.5*IQR]. With Q1 = 25% quartile, Q3 = 75% quartile, IQR = interquartile range.

Table 4
Average Euclidean distances between the four major sample clusters.

Cluster 2	0.69		
Cluster 3	1.20	1.34	
Cluster 4	1.14	1.58	0.93
	Cluster 1	Cluster 2	Cluster 3

was a common practise in the region during the main occupation phase of Çatal Oluk and persists up to the present day (Anderson and Ertug-Yaras, 1996).

Cluster 1 and 2, covering the central, northern and eastern areas of the site, both contain elevated values of Co, Cr, Fe, Mg, Mn and Ni. Geologically, these are all mafic and ultramafic elements typically

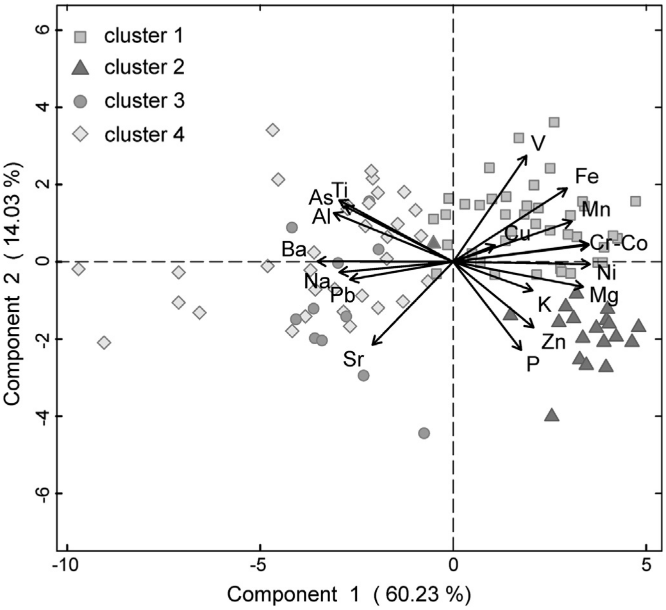

Fig. 7. Principal component scores (points) and scaled loadings (arrows) for the first two principal components. Principal component analysis was performed on the centred log ratio transformed dataset.

enriched in ophiolitic mélange deposits in the Sagalassos region (Muchez et al., 2008). However, the soils at Çatal Oluk are rich in limestone colluvium and are underlain by a flysch substrate. In addition, the drill core shows no evidence for a local change towards ophiolitic colluvium or bedrock. Thus, the observed anomalies of these elements are not attributed to natural variations. A clue for interpretation lies in the fact that ceramic production requires suitable clays as a raw material. In the territory of Sagalassos, all building ceramics (Degryse et al., 2003b) and most cooking and storage vessels created during Classical–Hellenistic to Byzantine times were produced out of ophiolitic clays (Neyt et al., 2012). When the ceramics themselves would be the source for the observed anomalies, one would expect a strong positive relation between the total amount of ceramics and the concentration of ophiolitic material. However, it can be deduced from Figs. 2 and 5 that this is not consistently the case. For example, in the northern part of the study site, the total amount of ceramics (calculated as the sum of the number of sherds and tiles) is low, while the soil samples in this area contain elevated concentrations of the mafic elements (Co, Cr, Fe, Mg, Mn and Ni). We performed a linear regression in an attempt to predict Cr concentrations as a function of the amount of ceramics. The calculated R^2 value is 0.17, indicating that Cr concentrations are poorly predicted by the number of ceramics. Regression models based on other mafic elements show similar results. A more likely hypothesis in this case is that the mafic anomalies reflect the clay raw material used to produce the ceramics, rather than the ceramics themselves. As no ophiolitic clays are present at Çatal Oluk, it is highly likely that they were exploited elsewhere, transported to Çatal Oluk and stored near the kiln locations. Hence, the elevated concentrations of Co, Cr, Fe, Mg, Mn and Ni probably result from ophiolitic clays being stored and worked on Çatal Oluk, both in the location of the ceramic-producing kilns, and on its surrounding fields. The relatively high number of sherds in the eastern fields might be an argument in favour of a more intensive use of this area when compared to the rest of the site, although a downslope redistribution of sherds originating from the central kiln area cannot be excluded.

In the remaining parts of the study area, magnetic data show a number of linear disturbances that might be interpreted as buried architectural remains. Conversely, the archaeological survey did not result in decisive arguments confirming the interpretation of Çatal Oluk as one large villa site or farming estate. Rather, the unbalanced functional distribution of the collected sherds and the lack of spatial focus indicate that at least part of the sherds in this area might reflect ancient manuring practises, in which ceramic refuse was included in the manure that was spread on the fields. Likewise, the chemical composition of the soils in this area does not show traces of focused human activity. Clusters 3 and 4, which have a clear spatial focus in the western and southern fields, are characterised by correlations of Al, As, Ba, Ca, Na, Sr, Ti and Pb. The association of Al, Ba and Pb was identified as a tracer signature for limestone soil in the Sagalassos territory (D'Haen et al., 2012). Also the higher levels of Ca and Sr in cluster 3 can be easily explained by increased limestone content in these samples. However, Ba, Sr and Pb display median concentrations significantly higher than median concentrations of the limestone and flysch deposits (Table 3). Although it is tempting to relate these enrichments to archaeological sources such as organic refuse disposal for barium (Parnell et al., 2002) or metallurgical activities for lead (Grattan et al., 2007), the more likely explanation in this case is the influence of volcanic tuff deposits on the soil composition. As mentioned in Section 3, large quantities of weathered Gölçük tuffs are present in the western and southern fields of the study area. This material consists of plagioclase, alkali feldspars and smaller amounts of, clinopyroxene, hornblende and biotite (Alıcı et al., 1998). Alıcı et al. (1998) and Muchez et al. (2008) have reported high to very high total concentrations of Ba, Sr and Pb in these tuffs (up to 4020 ppm, 5684 ppm and 142 ppm, respectively), resulting from substitutions in major and minor minerals. Elevated tuff content in the soils can thus easily explain the observed elemental anomalies. Overall, it can be concluded that the elements with a negative loading on the first principal component (As, Al, Ba, Na, Pb, Sr and Ti) can be considered geogenic elements, related to the combined contribution of limestone- and tuff fragments.

7. Discussion

Previous research has stressed the importance of integrating multiple survey strategies. However, multi-element chemical survey is only rarely included in archaeological survey programmes. The main goal of this paper was therefore to assess the advantages and limitations of this technique as a survey method, in combination with traditional strategies.

Our results demonstrate that, while it is indeed difficult to directly interpret chemical soil data in terms of ancient human activity (López Varela and Dore, 2010; Walkington, 2010), this survey technique does have potential to complement more common prospection techniques (Wilson et al., 2005). For example, in this study, the circular anomalies detected by the magnetic survey could more reliably be interpreted as kilns thanks to chemical anomalies of K, P and Zn. It is expected that geochemical soil survey particularly holds potential as a technique complementary to geophysical prospection. Not only can chemical information facilitate the interpretation of structures detected by geophysical techniques, it might also be used to help distinguishing between human and natural (e.g. changes in bedrock) causes for detected geophysical disturbances (Jordan, 2009).

In addition, this study illustrates the advantages of analysing a large elemental spectrum, instead of focussing on a limited suite of elements often quoted as potential indicators of ancient human activity (Bintliff et al., 1990; Parnell et al., 2002; Terry et al., 2004). In this study, the important anomalies of Co, Cr, Fe, Mn and Ni around the kiln area were only recognized because a large number of elements were analysed. They would have remained undiscovered if only typical elements associated with human occupation at archaeological sites, such as Cu, Zn, P and Pb, had been included in the analyses. When working with a larger number of variables, the value of multivariate techniques cannot be overestimated. They allow visualisation of patterns within the compositional data structure and allow for defining statistically significant groups, thereby significantly contributing to a comprehensive interpretation of the elemental distribution patterns (see discussion in Reimann et al. (2008)).

With respect to the research domain aiming to find typical elemental indicators of past anthropogenic activity, the results of this study are consistent with patterns discovered in other studies. Phosphorous remains the most straightforward indicator of human disturbance (Holliday and Gartner, 2007), and K and Zn have previously been linked to burning and excrement, respectively (Wilson et al., 2005; Oonk et al., 2009a). Our research also provides an extra argument in favour of using a strong acid digest when applying chemical prospection as an archaeological survey technique, over mild acid digests often suggested (Middleton, 2004). Not only is it possible that part of the anthropogenic chemical fraction is held within resistant soil phases (Wilson et al., 2008; Oonk et al., 2009b), our data also indicate that potentially useful chemical information can be contained within natural mineral phases, most of which are not dissolved using weak acid digests.

Finally, this research confirms the importance of taking into account the geological setting when prospecting for anthropogenic patterns, as suggested by Luzzadder-Beach et al. (2011). Without this, the high Pb, Sr and Ba concentrations in this study would have been erroneously interpreted as resulting from human activities, instead of reflecting the lithological influence of volcanic tuffs.

8. Conclusion

In the north-central area of the study site, the occurrence of strong circular magnetic anomalies combined with high surface concentrations of tiles and bricks, strongly suggest the presence of buried tile-producing kilns. On the same location, chemical enrichments of K, P and Zn are explained by burning of wood or dung as fuel for the kilns. Ceramic content and radiocarbon dating of a sediment core on this location suggest anthropogenic soil disturbance between 0 and 80 cm. Multivariate statistics reveal anomalies of Co, Cr, Fe, Mg, Mn and Ni on and around the detected kilns. Since a geological source for these anomalies is unlikely in this case, the enrichment patterns are thought to result from storage and working of ophiolitic clays, typically used as a raw material for tile production in this region. Al, As, Ba, Ca, Na, Pb, Sr and Ti are considered geogenic elements in this study. Local enrichments are explained by the combined contribution of limestone and volcanic tuff fragments.

The results of the present study demonstrate that soil chemical prospection holds potential as a surveying technique, as it was found that chemical data facilitate interpretation of structures detected by geophysical and archaeological methods, thereby creating an extra dimension in the interpretation of survey data. In addition, when applying soil geochemical survey as an archaeological prospection technique, a pseudo-total extraction technique and analysis of a large suite of elements is to be preferred over mild acid digests focussing on a limited number of elements, as potentially useful information can be contained within natural mineral phases. This research also confirms the importance of considering the geological setting when interpreting soil chemical data in terms of human inputs, as lithological changes can strongly influence concentration ranges. Multivariate statistics proved to be invaluable in distinguishing anthropogenic from lithological soil patterns.

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