High-resolution stratigraphy of Scandinavian coastal archaeological settlements: the case of Håkonshella, W Norway

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The stratigraphy of Scandinavian open-air archaeological settlements is usually characterized as homogeneous, highly enriched in decomposing organic matter and poor in biogenic carbonates such as shells or bones. As a result, stratigraphies are often difficult to read in the field and settlement sequences may pass unnoticed by archaeologists. Here we show how the integration of bulk analyses, soil micromorphology, X-ray fluorescence (XRF) core scanning and multivariate statistics can help in overcoming such limitations. We use the case study of Håkonshella 8, a Mesolithic hunter-fisher-gatherer settlement located in Bergen (W Norway). Fluctuations in the organic matter content, geochemical proxies (mainly P, Ga, Ti and the Si/Al ratio) and redoximorphic features highlight four cycles of site occupation and abandonment in an otherwise massive anthropogenic deposit. Following these settlement sequences, the site was covered by colluvium from nearby slopes over which a waterlogged soil formed. The approach used in Håkonshella has the potential to improve our capacity to interpret organically enriched anthropic deposits formed in coastal Scandinavia and in similar climatic regions.

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The need for pin-sharp screening tools to understand stratigraphical sequences is compelling in Scandinavian open-air coastal archaeological sites. In these contexts the sequences are usually shallow, massive black and highly enriched in decomposed organic matter, with almost no biogenic carbonate remains such as shells or bones. Postdepositional processes and diagenesis caused by soil acidity and leaching significantly alter the archaeological record and pose significant challenges in terms of excavation methodology, stratigraphical control and phasing of cultural deposits (Simpson 1999; Estévez et al. 2013). In these problematic situations, with some exceptions (Balbo et al. 2010a; Briz Godino et al. 2011; Villagrán et al. 2011), excavation often proceeds by artificial cuts of homogeneous deposits. Archaeological sequences are defined in post-excavation phases largely based on the combination of accelerated mass spectrometry (AMS) dating with the qualitative and quantitative study of archaeological materials (Olsen 1992; Bergsvik 2002; Ramstad 2005; Bjerkc et al. 2008).

X-ray spectrometers have been widely used in archaeometry to characterize archaeological materials such as minerals, rocks, sediments, pottery sherd, bones, paintings, glasses, coins and tokens, amongst others (Piga et al. 2009; Duran et al. 2011; Shilstein & Shalev 2011; Forouzan et al. 2012; Liu et al. 2012; Attaeulmanan & Mouton 2014; Columbu et al. 2014; Hunt & Speakman 2015). With some exceptions (Finlayson et al. 2006; Iriarte et al. 2013; Kalbe et al. 2014), XRF core scanning –closely spaced, high-resolution multi-elemental analysis of split sediment or rock slabs – has been much less applied in archaeological research. Mostly developed for the study of palaeoenvironmental records, XRF core scanning has become essential as a relatively fast, nondestructive method to precisely assess the geochemistry of sediment sequences extracted from wetlands (Poto et al. 2013; Martin et al. 2014; Schittekk et al. 2014), the sea floor (Frigola et al. 2007; Moreno et al. 2012) or the bottom of lakes (Unkel et al. 2008; Morellón et al. 2009; Calò et al. 2013), allowing detailed information on long-term climatic shifts and landscape evolution to be obtained. Due to its millimetric resolution, the application of XRF core scanning in archaeological contexts has great potential for identifying microstratigraphical layers related to settlement sequences virtually undetectable in the field.

Here we show the potential of combining established geoarchaeological techniques, such as soil micromorphology and bulk sediment analyses, with XRF core scanning and multivariate statistics to assess and differentiate the microstratigraphy of Scandinavian anthropic deposits. We use the case study of Håkonshella 8, an open-air, hunter-fisher-gatherer coastal Mesolithic settlement located to the W of Bergen, W Norway. The main aims of our study were (i) to refine our understanding of the site occupation phases, and (ii) to identify depositional and postdepositional processes that have contributed to the formation of the site.
Study area

Håkonshella 8 (UTM 32 289287 E–6696005 N) is located about 10 km W of Bergen, W Norway (Fig. 1A), at a small peninsula facing the strong tidal current Vatlestraumen towards the W. It is located near the cross-point of three fjord systems, Hjeltefjorden to the NW and N, Byfjorden to the NE and Grimstad-
fjorden, to the SE. The local climate is temperate oceanic, with a mean annual temperature in 2014–2015 of 7.5 °C (highest 31.4 °C and lowest −6.3 °C) and a mean annual precipitation of 2250 mm (climatic data retrieved from Bergen, Meteorologisk Institut). Geologically, the region falls within the Minor Bergen Arc, formed by three highly strained rock units: the Nordasvatn Complex (with metagabbro, amphibolite, greenstone and greenschist), the Storevet (a metasedimentary cover consisting of green polymict conglomerate) and the Gamlehauen Complex (formed by entangled psammitic metasediments and mylonitic gneisses) (Fossen 1989). The most common soils are podzols, characterized by a typically ash-grey upper subsurface horizon bleached by loss of organic matter and iron oxides, leading often to the formation of an albic horizon (FAO 2006). Conifers and broad-leaved trees abound, as well as holly and bell heather.

There has been extensive research on the Mesolithic of coastal Norway over the past 30 years (Bjerck 2008). The highest concentrations of Mesolithic settlements have been identified along the W Norwegian coast, where the presence of islands, inlets, skerries, bays and headlands provided more sheltered seascapes and richer marine biotopes than those found in continental Europe (Bjerck 2005). Most of the sites were shore-bound and coastal settlement areas were typically in use over periods of several thousands of years (Ramstad 2005). Such long settlement histories and the preservation of coastal sites were favoured in some portions of W Norway by the postglacial isostatic uplift of Scandinavia, which limited coastal submersion following Holocene deglaciation and the consequent sea-level rise (Bondevik & Svendsen 1998; Bailey & Flemming 2008; Balbo et al. 2010b). As a result of long settlement histories and local climatic conditions, anthropic layers within coastal Mesolithic sites appear as fat, dark, charcoal-rich massive deposits mixed with fire-cracked rocks and heavily decomposed bone material (Bjerck 2008).

Excavated between 2011 and 2012, Håkonshella 8 contained one of the earliest dated Mesolithic dwellings in W Norway (Bjerck 2008; Astveit 2009). Håkonshella 8 is now located 14 m a.s.l. due to isostatic uplift, but was shore-bound at the time of Mesolithic occupation. After mechanical stripping of the turf grown on top of the archaeological area, archaeological layers were excavated over 66 m², removing a total of 12.58 m³ of sediment. The removed sediments were water-sieved in 2–4 mm meshes. Neither organic material nor biogenic calcium carbonate remains were recovered during the excavation. The total number of finds was 12,249, consisting of tools and waste material from lithic production.

Material and methods

Sampling and physico-chemical analyses

The sampling was concentrated on a portion of the stratigraphical profile 47 cm thick and consisting of five superposed layers (0, 1, 2, 3, 12), including a Mesolithic floor. Layer 0 (0–12 cm below ground level; b.g.l.) was the current topsoil, black and highly enriched in organic matter. It was dotted with white fine material and abundant roots from the grass growing on top at the time of excavation. Layer 1 (12–17 cm b.g.l.) was characterized in the field as a black palaeosol, with little mineral component, clayish and fatty in texture. Layer 2 (17–22 cm b.g.l.) was dark grey and consisted of sand, abundant angular clasts and subrounded boulders. Layer 3 (22–37 cm b.g.l.) was interpreted as corresponding to the Mesolithic occupation, showing some mineral inclusions from layer 2 and strong bioturbation in the form of worm and root channels. It mostly consisted of homogeneous, massive reddish-brown sand mixed with charred material and highly decomposed organic matter. Finally, layer 12 (37–45 cm b.g.l.) was very dusky red and mainly composed of sandy and silty quartz grains. It was very bioturbated and partially mixed with layer 3, including also small weathered angular clasts (Fig. 1B).

Three sets of samples were taken from the exposed stratigraphy at Håkonshella 8, on which physico-chemical analyses were performed in the laboratory (Fig. 1B, C).

Bulk samples (BS) for loss on ignition (LOI) were collected bottom-up from the stratigraphical profile every 2 cm and burned for 4 h at 105, 400, 480 and 950 °C to estimate the proportion of water, organic matter, coal and calcium carbonate, respectively (Heiri et al. 2001).

Five undisturbed blocks for soil micromorphology (M1–M5), including intact strata and the transition between strata, were also taken from the stratigraphical profile using Kubiena boxes (10×8×8 cm). Thin sections were prepared at SCT Micromorfología de Sols i Anàlisis d’Imatges Laboratory, Universitat de Lleida, Spain. After drying for 2 months at room temperature, the collected undisturbed blocks were impregnated with a mixture of Palatal polyester with styrene (100–200 mL L⁻¹), MEK (5–7 mL L⁻¹) and two drops of cobalt octoate. Following impregnation, samples were left to dry for another 6 weeks. Thin sections were cut with a diamond blade and polished with a machine Brot Tech® 1.03.12.P until a thickness of 20 μm was achieved. Analysis of thin sections was carried out with Leica® MZ9.5 and DM2500 microscopes, as well as with a Keyence® VHX-2000. The micromorphological description and interpretation...
were based on Courty et al. (1989), Stoops (2003) and Stoops et al. (2010).

A continuous and undisturbed sediment sample across the stratigraphical profile (8–45 cm b.g.l.) was collected using an aluminium box (C1, 37×4×4 cm), which was encased in plastic film and aluminium wrap and stored in cold conditions before analysis. C1 was scanned at a resolution of 5 mm using an AVAATECH X-ray fluorescence core scanner equipped with a Rh tube at the XRF Core Scanner Laboratory of the Marine Geosciences GCR, Departament d’Estratigrafia, Paleontologia i Geociències Marines, Universitat de Barcelona. The core was covered with a 4 μm thin SPEXCert® Ultralene foil to avoid contamination and desiccation of the sediment during the measurements. The XRF core scanner was set at 10- and 25-s measurement times, 10 and 30 kV X-ray voltages, and 1.4 and 2.0 mA X-ray currents for major and trace elements, respectively. Layer 0 (8–12 cm) and the bottom of layer 12 (42–45 cm) were not scanned due to the poor preservation of the material in the core. Raw elemental data obtained after XRF core scanning were processed using the WIN AXIL (Analysis of X-ray Spectra by Iterative Least square) package from Canberra Eurisys to collect intensity data in counts per second (cps). In order to correct for changes in porosity and lithology along the core, we normalized the cps for each element by the total counts at each depth interval of all elements except Ag and Rh, which tend to be biased by the signal generation (Cuven et al. 2011; Bahr et al. 2014). We also used log-ratios to account for a robust representation of elemental ratios (Weltje & Tjallingii 2008; Grützner & Higgins 2010), selected to precise enrichments and depletions of mobile elements and diagenetic processes against detrital input. Al was chosen as a normalization element due to its acceptable counts along the core (mean of 161.0, 1254.08 at a 95% confidence interval) and its proven suitability in sedimentary sequences with strong fluctuations in the organic matter content (Löwemark et al. 2011), as for Håkonshella (Figs 2, 3). The final data set retained for analysis included eight elements (Al, Si, P, K, Ti, Ga, Rb and Zr) and five elemental ratios (Fe/Al, Mn/Fe, Si/Al, K/Al and Zr/Rb) and can be found in Table S1 and Figs 2, 3.

Data analyses

Factor analysis (FA) was carried out on the eight retained elements using XLStat® Pro version 2015.2. The aim was to explain the covariance between elements, identify underlying latent variables and reduce them to their common factor patterns. The Bartlett’s test (p<0.05), the Kaiser–Meyer–Olkin measure of sampling adequacy (KMO, 0.71) and the Cronbach’s alpha (0.82) indicated that the data set was factorizable and showed a high internal consistency (Cronbach 1951; Kaiser 1974). We thus ran the FA with a principal component extraction method after standardizing the data set to zero mean and unit variance. As communalities for each variable were >0.73, we assumed that more than three quarters of each variable’s variance was accounted for by the factor solution. We

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**Fig. 2.** Correspondence between the sediment core (C1), stratigraphy (La), thin sections (TS, M1–M5) and description of the thin sections. This figure is available in colour at http://www.boreas.dk.
retained for analysis factors 1 and 2, as they had an eigenvalue higher than 1 and accounted for more than 80% of the cumulative variability, thus fulfilling two important conditions for a factor analysis (Kaiser 1960; Jolliffe 2002). A Varimax rotation with Kaiser normalization was applied to minimize the number of variables with a high loading on each component and ease the interpretation of variable–factor correlations (Kaiser & Rice 1974). The rotated solution had no outliers (scores higher or lower than ±3) and exhibited ‘simple structure’, indicating that each variable strongly loaded on just one single factor (Thurstone 1947).

Radiocarbon dating

The chronological characterization for the Mesolithic occupation of Håkonshella 8 was carried out using AMS. Dating was performed at Tandem Laboratory, University of Uppsala, Sweden, and at Beta Analytic on hazelnut remains extracted from the sediment sequence near transition boundaries between different sediment deposition phases. Dates were calibrated using OxCal v4.2 (Bronk Ramsey 2009) and the IntCal13 calibration curve (Reimer et al. 2013) (Table 1).

Results

Loss on ignition

The organic matter content of layer 1 (79–71%) was significantly ($p \leq 0.0001$) higher than those of layers 2 (3–5%) and 3 (11–22%). Layer 2 showed the highest content of silicate residue (96–93%), whereas CaCO3 contents were negligible throughout the stratigraphical profile (<0.03%). As organic matter values along layer 3 seemed to roughly concur with peaks in P, Ga and the Si/Al ratio after visual inspection of the XRF data set (Fig. 3), we averaged the XRF data every 2 cm in layer 3 to correlate with the corresponding 2 cm from the LOI samples. The results indicated that organic matter correlated moderately and positively with the Si/Al ratio ($r = 0.56, p = 0.14$), strongly and negatively

![Graph](image-url)

**Fig. 3.** Results of the physico-chemical analyses. Values for individual elements have been normalized by the total counts at each depth interval for all elements except Ag and Rh. Elemental ratios have been normalized as ln(ratios). This figure is available in colour at http://www.boreas.dk.

Table 1. AMS dates.

<table>
<thead>
<tr>
<th>Lab. code</th>
<th>Layer</th>
<th>Sample</th>
<th>Weight (g)</th>
<th>$^{14}$C a BP</th>
<th>Cal. 1 sigma BC</th>
<th>Cal. 2 sigma BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ua-44660</td>
<td>2</td>
<td>Hazelnut</td>
<td>0.29</td>
<td>4594±42</td>
<td>3498–3139</td>
<td>3516–3108</td>
</tr>
<tr>
<td>Ua-44659</td>
<td>2</td>
<td>Hazelnut</td>
<td>0.26</td>
<td>6678±48</td>
<td>5639–5558</td>
<td>5701–5511</td>
</tr>
<tr>
<td>Ua-44668</td>
<td>5</td>
<td>Hazelnut</td>
<td>0.21</td>
<td>5997±40</td>
<td>4942–4837</td>
<td>4993–4791</td>
</tr>
<tr>
<td>Ua-44677</td>
<td>5</td>
<td>Hazelnut</td>
<td>0.20</td>
<td>7643±47</td>
<td>6561–6440</td>
<td>6591–6431</td>
</tr>
<tr>
<td>Ua-44666</td>
<td>11</td>
<td>Hazelnut</td>
<td>0.20</td>
<td>6677±42</td>
<td>5636–5560</td>
<td>5666–5521</td>
</tr>
<tr>
<td>Ua-44665</td>
<td>3</td>
<td>Hazelnut</td>
<td>0.22</td>
<td>7113±42</td>
<td>6030–5924</td>
<td>6062–5903</td>
</tr>
<tr>
<td>Ua-44664</td>
<td>3</td>
<td>Hazelnut</td>
<td>0.16</td>
<td>6611±42</td>
<td>5615–5514</td>
<td>5620–5486</td>
</tr>
<tr>
<td>Ua-44663</td>
<td>3</td>
<td>Hazelnut</td>
<td>0.06</td>
<td>7726±55</td>
<td>6604–6492</td>
<td>6647–6463</td>
</tr>
<tr>
<td>Ua-44662</td>
<td>3</td>
<td>Hazelnut</td>
<td>0.21</td>
<td>6804±41</td>
<td>5725–5662</td>
<td>5746–5630</td>
</tr>
<tr>
<td>Beta-344208</td>
<td>19/12</td>
<td>Hazelnut</td>
<td>0.14</td>
<td>7860±40</td>
<td>6766–6642</td>
<td>6984–6597</td>
</tr>
<tr>
<td>Ua-44661</td>
<td>14</td>
<td>Hazelnut</td>
<td>0.52</td>
<td>6816±48</td>
<td>5735–5661</td>
<td>5790–5629</td>
</tr>
</tbody>
</table>
with Ga ($r = -0.81$, $p = 0.015$), and had a very weak negative correlation with P ($r = -0.16$, $p = 0.69$).

**Soil micromorphology**

The layers differ in their degree of coarse and fine material, pedality and abundance of phosphates and iron pedofeatures. Layer 0 represents the current soil surface and is characterized by a granular microstructure and a double-spaced equal/coarse enaulic c/f-related distribution, with the coarse material decreasing downwards (Fig. 4A). The mineral fraction is entirely lacking in layer 1, which fully consists of mammillated, unaccommodated, moderately to strongly developed subangular blocky peds up to 2000 µm in diameter formed by highly decomposed organic matter (Fig. 4B). Frequent anthers about 300–500 µm in diameter containing hundreds of pollen grains (20–30 µm wide) were also identified in layer 1 (Fig. 4C, D). The coarsest material was found in layer 2, formed by dominant subangular and subrounded polycrystalline quartz grains (up to 5 mm in diameter) with sutured crystals, dominant K-feldspar (orthoclase) and frequent pebbles, very few plagioclase feldspar and shales (Fig. 4E–H). Such minerals are also present in layers 1, 3 and 12, although in much smaller amounts. Signs of weathering are clearly visible in microfacies 2a, with some minerals showing parallel linear and cross-linear patterns of alteration. Layer 3 mainly differs from layers 1–2 by the higher frequency of iron and phosphate impregnative pedofeatures. Phosphate nodules, mostly vivianite (appearing as

![Fig. 4. Correspondence between thin sections (TS, M1–M5), layers (La) and location of the photomicrographs (red squares), taken under plane polarized light (PPL) and cross-polarized light (XPL). A. Groundmass from layer 1, showing a granular microstructure and a double-spaced equal enaulic c/f related distribution (PPL). B. Boundary between layer 0 (top) and 1 (bottom). Note the lack of coarse material and the well-developed subangular blocky peds in layer 1 (XPL). C. Anthers, probably of *Alnus* sp. (PPL). D. Detail of the pollen grains within the anther shown on C. (XPL). E. Groundmass of layer 2 (XPL). F. K-feldspar (orthoclase) in layer 2. Note the cracks along crystallographical planes (cleavage) (XPL). G. Shale in layer 2. Note the breaks along laminations, parallel to the bedding, and the presence of very fine sand grains embedded in the rock (XPL). H. Plagioclase feldspar with characteristic twinning in layer 2 (XPL). I. Groundmass of layer 3 with aggregates and coarse material moderately to strongly impregnated by iron (PPL). J. Phosphate nodules (green colour) associated with iron impregnative pedofeatures, pointing towards vivianite (PPL). K. Phosphate impregnation of a polycrystalline quartz grain (PPL). L. Same as K. (XPL). M. Fragmented charcoal in layer 3 (PPL). N. Groundmass of the lowermost part of layer 3, showing clay nodules and strongly impregnated clay pedofeatures (PPL). O. Detail of microfacies 12a, composed of coarse to medium sand grains with no fine material (XPL). P. Groundmass of layer 12, showing strongly impregnated iron pedofeatures, fine material and phosphate nodules. This figure is available in colour at http://www.boreas.dk.]}
radial aggregates with a greenish-blueish colour under plane-polarized light), were identified with moderately to strongly impregnated iron pedofeatures, quartz grains and highly decomposed organic matter (Fig. 4I–L). Iron coatings and hypocoatings were also identified in thin sections from layer 3, as well as fragments of plant remains and clay-replaced plant tissues (Fig. 4M, N). Layer 12 is separated from layer 3 by microfacies 12a, which has a massive structure, very dominant subangular and subrounded polycrystalline quartz grains up to 500 μm in diameter and very little organic matter. Phosphate nodules and iron impregnative pedofeatures, although lacking in microfacies 12a, appear again in layer 12 along with finer material and more organic matter (Fig. 4O, P).

**Geochemistry**

Figure 3 shows the results from the XRF core scanning. The down-core fluctuation of the analysed elements clearly corresponds with four out of the five layers identified in the field on the basis of their composition, colour and structure. The transition between layers 1–2 is characterized by an increase in Al, Si, K, Rb, Zr and Mn/Fe and by a decline in Fe/Al, Si/Al, K/Al and Zr/Rb. Layer 3 shows a marked increase in P, Ti, Ga and Fe/Al in relation to layer 2, as well as a slight increase in Zr/Rb and K/Al at the topmost part of the layer. It also appears depleted in Mn/Fe compared to layer 2. The transition between layers 3 and 12 does not clearly show any change in the pattern of any variable.

Figure 5A presents the variations of the factors (Fs) against composite depth, vertically displaying the contribution of each of the 61 observations to the new vectorial space defined by the FA (Morellón et al. 2009; Ferro-Vázquez et al. 2014), whereas Fig. 5B reports the correlations between the variables and each factor (F), respectively. We retained for analysis F1 (eigenvalue of 4.43) and F2 (eigenvalue of 2.58), which
accounted for 87.8% of the variability. High positive F1 scores characterize layer 2, whereas high positive F2 scores were attained throughout layer 3 and the topmost part of layer 12, with four clear peaks at 25, 28, 32 and 36 cm b.g.l. The relationship between the observations in the layers and the variables is also sharply visible in a biplot (Fig. 5C), with F, Ti and Ga clearly associated with layers 3 and 12 and Al, Zr, Rb, K and Si linked to layer 2.

**Radiocarbon dating**

The radiocarbon dates obtained from layer 3 indicated a Mesolithic occupation spanning 6647–6463 to 5620–5486 BC (2σ) (Table 1).

**Discussion**

The discussion will focus on layers 1–12, top to bottom. Layer 0 will not be considered as it represents the current soil surface and was not scanned through XRF.

**Mineral and organic matter**

F1, which explained 55.33% of the variability, is interpreted as ‘mineral input’ due to high positive contribution of variables related to siliciclastic deposits, such as Al, Si, K, Rb and Zr. Higher positive F1 scores thus reflect higher clast contents (layer 2), whereas higher negative scores indicate a lack of coarse material and predominance of organic matter (layers 1 and 3).

The elements that positively contribute to F1 are found in sandstones, feldspars and shales, which were widely identified in thin sections from layer 2 (Fig. 4E–H). K is found in orthoclase feldspars, whereas Zr and Rb tend to respectively be enriched in coarser (e.g. quartz, feldspar) and finer grains like clay materials (e.g. claystones, shales). The Zr/Rb ratio has thus been traditionally used as a granulometry proxy, with higher ratios pointing towards coarser-grained units and lower ratios reflecting finer-grained material (Dypvik & Harris 2001; Chen et al. 2006). Although it has been generally assumed that Zr/Rb ratios are not significantly altered by postdepositional weathering, some studies have found that Rb is much more mobile than Zr and that it can be lost from the profile when chemical alteration of K-feldspar minerals is high (Hodson 2002; Liu et al. 2006). Rb can also substitute for K in the crystal lattice of K-feldspars, which are commonly associated with coarse silt and sand fractions (Wedepohl 1971; Kylander et al. 2011), thus lowering the Zr/Rb ratios in coarse-sized layers. Under these circumstances the Zr/Rb ratio is unreliable as a proxy for granulometry.

K-feldspar diagenesis seems to have been an important process on the topmost horizon of layers 1, 2 and 3. This is suggested by low K/Al ratios, which have been used as a proxy for severe chemical diagenesis (Hu et al. 2013; Clift et al. 2014), with lower ratios suggesting higher weathering of K-feldspars (Fig. 3). Micromorphological signs of weathering such as parallel linear and cross-linear patterns of alteration in microfacies 2 also point towards K-feldspar dissolution (Fig. 4E). Moreover, the strong and significant \( r = 0.97, p < 0.0001 \) correlation between K and Rb throughout C1, along with the lack of correlation of Ti with K \( r = -0.05, p = 0.68 \), respectively indicate that K-feldspars might be a major source of Rb and that fine grains might not be relevant hosts for Rb (Kylander et al. 2011). This explains why the highest Zr/Rb ratios are not found in layer 2 but in layers 1 and 3, despite the former being coarser and comparatively enriched in the mineral fraction in thin sections. The lack of fine material and soil aggregates within layer 2, along with the absence of the main micromorphological features related with solifluction deposits (well-developed preferred clasts orientation perpendicular to contours and platy structure), suggest that layer 2 formed after an energetic event of erosion and deposition (Fig. 4E–H).

Mn/Fe ratios have been regarded as a proxy for reoxidomorphic conditions, with lower values usually indicating anoxic environments (Davidson 1993; Koenig et al. 2003; Haenssler et al. 2014). Low Mn/Fe ratios are found in organic-rich layers such as 1 and 3, whereas higher ratios characterize layer 2. The latter is explained by the detrital nature of layer 2: with all other things being equal, the deposition and diagenesis of Mn-bearing rocks such as sandstones and shales lead to an increase in the Mn content of the sediment, therefore increasing the Mn/Fe ratio. In any case, organic matter tends to decrease the soil redox potential in wet soils both in absolute and relative terms, as humic substances are key in immobilizing Fe and Mn following reduction to soluble Fe\(^{2+}\) and Mn\(^{2+}\), respectively (Graham et al. 2002; Gardiner & James 2012). This concurs with low Mn/Fe values in layers 1 and 3, indicating a lack of air and waterlogging. The peak in Fe/Al at the top of layer 1 probably resulted from the precipitation of Fe to FeCO\(_3\), leading to a redox enrichment where the water table fluctuated (Schitteke et al. 2014). Layer 1 was thus probably a seasonally waterlogged soil formed in situ with negligible contribution of sediments from the surrounding slopes, as indicated by negative F1 scores, scarcity of minerals within the groundmass and its moderate to strongly developed subangular blocky pedds. Anthers present in layer 1 point towards *Alnus* sp. (W. Out, pers. comm. 2013), a genus comprising about 30 species of monocious trees and shrubs common in palustrine, lacustrine and wet landscapes (Fig. 4C, D). Both the abundance and the size of the anthers suggest that they were local in origin.
Anthropic activity

F2, which explained 32.46% of the variability, is interpreted as ‘anthropic activity’ due to the high positive contributions of variables that can be linked to human influence, such as P, Ga and Ti. High positive F2 scores are found in layer 3, with four clear peaks at 25, 28, 32 and 36 cm b.g.l., probably representing at least four different occupation phases between 6467–6463 and 5620–5486 BC (2σ). The highest negative F2 scores are found in layers 1–2, indicating the end of the settlement. Scores close to zero are attained along layer 3 and were interpreted as temporary abandonments of the site (Fig. 5).

P has been widely used in archaeology as an anthropic proxy, as prolonged human occupations increase soil P as a result of burning of organic material, accumulation of human and animal waste, deposition of ash from hearths, decomposition of food remains, deposition of burials and/or fertilization (Bethell & Máté 1989; Holliday & Gartner 2007). When humans add P to the soil, it mostly accumulates at the site of deposition, and it is less susceptible to leaching, oxidation, reduction or plant uptake than other elements such as C, N, S or Mg (Holliday & Gartner 2007). As layer 3 showed 65.52 times more P cps than layer 1 and four to seven times less organic matter, we considered human activity to be the most plausible factor responsible for the enhancement of P in layer 3. In this context, vivianite, whose presence was confirmed in thin sections from layer 3, is a Fe-phosphate mineral that has been related to human waste in archaeological settings (Karkanas & Goldberg 2010). It is very stable under anoxic conditions (Mirot et al. 2009) and indicates that layer 3 was poorly oxygenated and enriched in Fe (McGowan & Prangnell 2007).

The other elements that contributed positively to F2 are Ga and Ti. Ga is a relatively stable trace element that can be found in fields or micas, in soils associated with Fe and Mn hydroxides, in the atmosphere (although in very low concentrations) and in plant and human tissues (Kabata-Pendias & Mukherjee 2007). Significant amounts of Ga can also enter the soil as fly ash during or after combustion activities (Katrak & Agarwal 1981; Kabata-Pendias & Mukherjee 2007; Zhao et al. 2010; Mayfield & Lewis 2013). Ti is rather immobile in soil profiles and is usually associated with clay mineral assemblages. Due to their stability and their capacity to be transported by different natural agents (e.g. wind, water) in different grain sizes, both elements have been regarded as proxies for dust or sediment input related to soil erosion caused by deforestation and/or other land-use changes (Hölzer & Hölzer 1998; Kempter & Frenzel 1999; Fábregas Valcarce et al. 2003; Martínez Cortsizas et al. 2005). In the case of Hákonshella, the lack of correlation between Ga and Al, K, Mn or Fe ($r < 0.16, p > 0.29$) indicated that fluctuations of Ga along layer 3 were most likely not driven by edaphological factors or mineral inputs from the surrounding slopes. The latter also applied to Ti, which showed a different pattern to those of Al and Si ($r < 0.25, p > 0.17$). Whereas Al and Si were highly correlated ($r = 0.84, p < 0.0001$) and precisely reflected the variations in the input of coarse material along C1, as confirmed by thin sections and FA, Ti contents in the coarsest deposit (layer 2) were as low as in layer 1, which showed the finest texture. This suggests that Ti entered the stratigraphy through a different depositional agent from that of Al or Si. We hypothesize that higher Ga and Ti contents in layer 3 mainly entered C1 as dust particles during periods of higher anthropic activity and transformation of the surrounding landscape, probably leading to forest clearances and destabilization of the soil. Although at a lower resolution (five samples, one every 3 cm), pollen analyses from the same stratigraphical sequence indicated significant fluctuations in pollen grains from Alnus, Coryla and Betula (from 30 to 10%) along layer 3 (Overland 2013), probably reflecting changes in forest composition caused by humans in the Mesolithic period.

Si/Al or Si/Ti ratios – the former contributing negatively to F2 – have been widely used as a proxy for biogenic silica, e.g. phytoliths and diatoms (Brown et al. 2007; Brown 2011; Stolze et al. 2012). Phytoliths, microscopic silica bodies produced by plants, have been consistently found in archaeological settings, often indicating in situ processing of plants (Piperno 1988, 2006). Diatoms, unicellular algae organisms occurring in freshwater and marine environments, have previously been found in various archaeological contexts, including in buildings where they indicate the use of turf (Bathurst et al. 2010), in agrarian terraces (Trombold & Israde-Alcantara 2005), embedded in the clay used to craft pottery (Matiskainen & Alhonen 1984; Battarbee 1988) and in the filling of canals (Purdue & Berger 2015). The Si/Al values and F2 scores recorded here are strongly negatively correlated ($r = −0.78, p < 0.0001$), the four highest peaks in the Si/Al ratio matching the four lowest scores for F2 (Fig. 6). Although somewhat counterintuitive, this points towards more deposition of biogenic silica during periods of site abandonment rather than during site frequention. This might be explained by the re-wetting of the ground and subsequent plant colonization following the periodical abandonments of the settlement, a context that might have favoured a higher deposition of diatoms and phytoliths. The alternation between drier and wetter conditions as cycles related to intervals of occupation and abandonment also explain the comparatively higher presence of redoximorphic features in thin section in layer 3, which indicate changes in the oxidation state of the groundmass (Lindbo et al. 2010).
More information is needed in order to clarify whether climatic shifts were the main factor determining the frequentation/abandonment phases of the Håkonshella hunter-fisher-gatherer settlement. The data available to date do not allow to rule out alternating wet and dry conditions being the result of settlement phases rather than changing climatic conditions, with fires, hearths and site caring temporarily drying out the ground during periods of occupation. In either case, the first hunter-fisher-gatherers in Håkonshella settled directly on the beach surface, as suggested by the coarse nature of microfacies 12a, which shows abundant quartz sand grains and phosphate nodules.

Conclusions

The integration of XRF core scanning with bulk analysis, soil micromorphology and multivariate statistics allows phases of occupation in Scandinavian open-air coastal archaeological settlements to be distinguished, even in homogeneous deposits lacking biogenic carbonate remains and discriminant macrobotanical remains. Authigenic enrichments and depletions of mobile elements can also be identified, providing critical information on diagenesis, anthropic inputs and site formation processes. At Håkonshella we identified four intervals of site occupation and abandonment during the ~1000 years of Mesolithic settlement (6647–6463 to 5620–5486 BC (2σ)). Periods of occupation were characterized by peaks in P, Ga, Ti and higher redoximorphic features. Stages of abandonment were associated with higher Si/Al ratios and organic matter inputs, probably reflecting the periodical return of the natural vegetation and the re-wetting of the site. The definitive abandonment of the settlement was followed by fast burial by colluvium, indicating slope erosion possibly due to changing climatic conditions or loss of vegetation cover. Later, the depression in which the site lies was filled with water for significant periods of time, allowing the formation of a seasonal pond surrounded by hygrophilous plants (probably Alnus sp.). These two depositional events contributed to the isolation of the Mesolithic layer from external disturbances, allowing the chemical signals related to the settlement sequences to be preserved through time.

The refinement of our understanding of settlement sequences in massive organic rich deposits has great potential to improve the interpretation of cultural layers in open-air coastal Scandinavian archaeological sites. In the case of Norwegian Mesolithic societies, this will lead to enhanced insights into mobile settlement patterns and site-occupation frequencies, thus contributing to our knowledge on the degree of sedentariness of specialized Mesolithic maritime societies. From a methodological standpoint, the application of XRF core scanning in archaeological settings will probably enhance sampling precision, as microstratigraphical layers containing traces of human activity are likely to be identified. Being a relatively fast, non-destructive technique, the data obtained through XRF core scanning may also be useful for archaeologists to re-arrange digging strategies while still in the field.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at [http://www.boreas.dk](http://www.boreas.dk).

Table S1. XRF data set.