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ORIGINAL PAPER

Divergence, diet, and disease: the identification of group identity, landscape use, health, and mobility in the fifth- to sixth-century AD burial community of Echt, the Netherlands

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Abstract

This study aims to better understand the development of group identity, mobility, and health in the Early Medieval Meuse Valley. This is achieved by combining existing demographic and palaeopathological information from 73 cremation deposits from Echt, the Netherlands, with new strontium isotope ratios ($^{87}Sr/^{86}Sr$) and strontium concentrations ([Sr]) that are performed on pars petrosa, diaphysis, and rib fragments. Although the surrounding Early Medieval cemeteries practiced inhumation, the initial burial community of Echt persisted in expressing the divergent burial ritual of cremation. Thirty-two radiocarbon dates demonstrate the fifth- to sixth-century cremation deposits to be chronologically separated from the seventh-century inhumations that were preserved in situ, suggesting a subsequent burial community replaced cremation with inhumation in the seventh century. Nutritionally inadequate diets may have contributed to the relatively high prevalence of porotic hyperostosis (~ 34%), resulting from decreasing foods supplies caused by deteriorating climatic conditions. The inhabitants are postulated to have mainly consumed foods originating from the land directly surrounding their farmsteads, expressed by the great variability in the $^{87}Sr/^{86}Sr$ of the diaphyses and ribs (0.7096 to 0.7131), matching the geological complexity of the area. The lack of significant differences between the $^{87}Sr/^{86}Sr$ and [Sr] of ribs and diaphyses connotes little change in the geological origin of the foods occurred over time, stressing the importance of the yield of local harvests. In contrast, large differences in childhood (i.e. pars petrosa) vs. adult (i.e. ribs and diaphyses) $^{87}Sr/^{86}Sr$ suggest the regional movement of individuals to possibly support inter-farmstead relationships (e.g. via marriages).

Keywords Cremation · Meuse Valley · Strontium isotope ratios · Strontium concentrations · Post-Roman · Early Medieval

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Introduction

In the Early Middle Ages, the Meuse Valley was one of the main axes of northern Francia. After the disintegration of the western Roman Empire, this peripheral region experienced significant population decrease, but "re-colonization" took place from the fifth to sixth centuries AD onwards, characterizing the landscape by dispersed farmsteads, located at varying distances from each other (Theuws 2019; Annaert 2018). In this periphery, far from any political and religious aristocracies, a free peasant society of possibly mixed origins seized the opportunity to establish its own group identity as part of the so-called Franconization process, which was visible as changes in material culture and also burial rites (Tys 2018; Annaert 2018; Theuws 2010). Despite a presumable lack of nucleation, the use of a single cemetery is suggested to have been a central element that characterized a group of individuals as burial community (Theuws 1998). Early Medieval cemeteries are consequently considered as central places, where social interaction and ritual activities strengthened the relationships between the families and communities that used the burial grounds (Härke 2011; Williams 2002).

In the recovery excavation of 2014–2015 that preceded building activities in the Echt-Bocage area, the Netherlands, an Early Medieval cemetery situated on the right bank of the Meuse river was excavated (Fig. 1). Based on the typology of the pottery found in the burial pits, 73 cremation deposits from the Echt cemetery were initially dated to the fifth to sixth centuries AD, while 2 cremation deposits were dated to the Iron Age (Verhoeven 2015). In addition, 75 inhumation graves were observed dating to the seventh century AD and were preserved in situ, but the total number of inhumations present was estimated to be at least 250 (Verhoeven 2015). The 73 Early Medieval cremation deposits were more or less clustered in the centre, while the inhumation graves surrounded this cluster. One Iron Age cremation deposit was retrieved outside the Early Medieval cluster, while the other was located within the cluster (see excavation map in Verhoeven 2015).

A number of Early Medieval cemeteries were excavated in the immediate vicinity of Echt (Fig. 1), such as Posterholt-Achterste Voorst (De Haas and Theuws 2013), Obbicht-Oude Molen, Stein, and Sittard-Kemperkoul (Kars et al. 2016), Ophoven-Hogekamp (Roosens 1976), Stokkem-De Kommel (De Winter and Wesemael 2014), Maasmechelen-Mottekamp (Steenhoudt and Smeets 2018), and some further away, such as Wijchen (Heeren and Hazenberg 2010), Alphen (Verhoeven and Janssen 2019), Uden (Knippenberg and Theuws 2019), Bergeijk (Theuws and Van Haperen 2012), Lutlommel (Van Bostraeten 1965), and Rosmeer (Roosens et al. 1976). Although some cremated remains were retrieved (e.g. Posterholt $n = 3$; Obbicht $n = 1$; SI 1), the main funerary rite in the region clearly was inhumation. Compared to the other Early Medieval cemeteries, the clustering and the large number of cremation deposits in Echt is remarkable and unique.

Why did the main burial rite in Echt, cremation, deviate from the purported main funerary practice, inhumation, in the surrounding cemeteries? During the Early Middle Ages, cremation was still practiced but seems to have been regionally spread with a remarkable appearance in the Scheldt Valley in Belgium and northern France. However, cremation graves were present as a minority at the inhumation burial grounds. In those bi-ritual cemeteries, cremation chronologically appeared from the fifth to seventh centuries, and the cremation deposits were scattered between the inhumation graves (Annaert et al. 2011). The Echt cemetery clearly shows a different picture. There is a chronological difference between the older cremation deposits and the younger inhumations, whereby both groups of graves are separated from each other spatially. The cremation deposits from Echt, therefore, provide a unique opportunity to investigate the dynamics of Early Medieval burial communities in the Meuse Valley.

The aim of this paper is twofold. Firstly, landscape use and mobility of the Echt burial community is evaluated by combining demographic information on the cremation deposits with strontium isotope ratios ($^{87}Sr/^{86}Sr$) of three skeletal elements with different overall bone turnover rates (i.e. the otic capsule of the pars petrosa, rib, and diaphysis). $^{87}Sr/^{86}Sr$ measured in human and animal bone, and teeth record the geographic origin of their foods, which take up their strontium mostly from the lithological composition of the soils they were growing on (Bentley 2006; Montgomery 2010), and are more and more commonly applied to cremated human remains (e.g. Snoeck et al. 2016, 2018, 2020A; Cavazzuti et al. 2019; Grupe et al. 2020; Taylor et al. 2020). Due to differences in bone turnover rates, each skeletal element represents a different time period in life enabling the observation of possible mobility during life (Clarke 2008; Fahy et al. 2017). The otic capsule contains childhood $^{87}Sr/^{86}Sr$ due to its virtually inhibited bone turnover rate (Veselka et al. 2021; Perlmann 1939). Ribs have a relatively high proportion of trabecular bone and, therefore, are suggested to have a higher bone turnover rate than diaphyses, which have a relatively high proportion of cortical bone (Parfitt 2002; Fahy et al. 2017). However, more research is needed to better understand Sr turnover rates in human bone apatite. Secondly, demographic and paleopathological information is combined with strontium concentrations ([Sr]) to investigate the possible influence age, sex, and pathological anomalies had on overall diet. The multi-faceted approach of this study improves our understanding of landscape use, mobility, diet, and health in Early Medieval burial communities in the Meuse Valley.

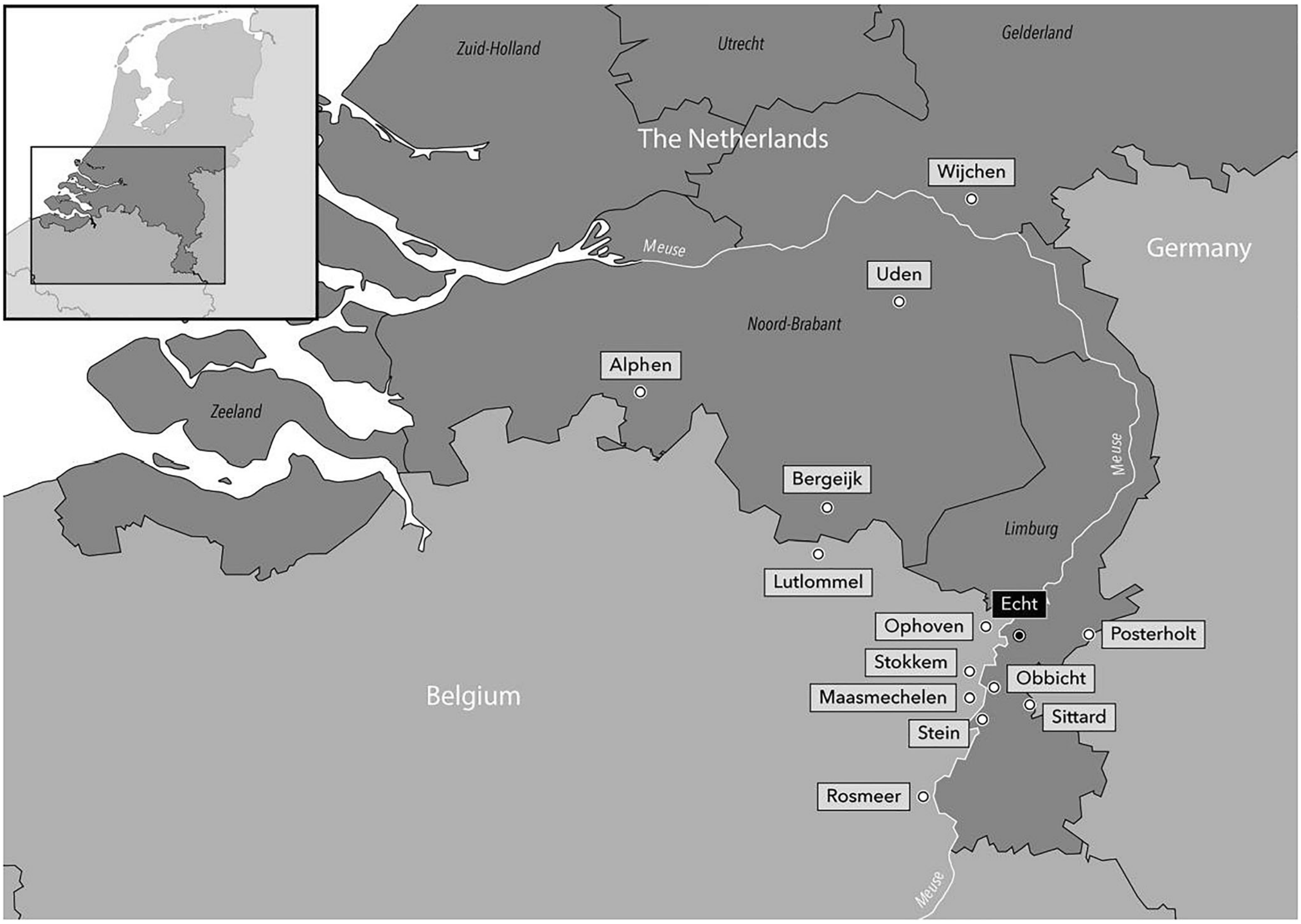


Fig. 1 Location of Echt and the Early Medieval cemeteries of Alphen, Bergeijk, Lutlommel, Maasmechelen, Obbicht, Ophoven, Posterholt, Rosmeer, Sittard, Stein, Stokkem, Uden, and Wijchen

Materials and methods

A total of 64 burial pits were excavated at the cemetery of Echt (Bocage area), the Netherlands. Eleven of these burial pits contained two cremation deposits, and one pit contained three burnt bone deposits, yielding a total of 75 cremation deposits. Four of these cremation deposits were buried in an urn. Based on the presence of Early Medieval pottery in the burial pits, 62 of these graves (with a total of 73 cremation deposits) were dated to the fifth to sixth centuries. Two of the urns were typologically dated to the Early Iron Age (800–600 BC; Verhoeven 2015). All the cremation deposits were analysed osteoarchaeologically in 2017, and an overview of the demographic results is provided as supplementary information (Veselka 2017; SI 2). A relatively high prevalence of porotic hyperostosis (PH; 33.3%; 14/42), a non-specific stress marker visible as diffuse porosity of the cranial vault, was observed in the Early Medieval cremation deposits (Veselka 2017; SI 3). To determine which factors may have influenced the occurrence of PH in the Echt cemetery, binary logistic regression analysis was used. The independent variables were age (nonadult vs. adult), sex (female vs. male), and new periosteal bone formation (NPB), scored as either present or absent. NPB is another non-specific stress marker, which was frequently observed on the lower limbs (10.4%; 5/48). Assessing the relationship between the two non-specific stress markers, PH and NPB, could provide further information on their aetiology. The dependent variable was PH (either present or absent). Logistic regression allows evaluation of the influence of each independent variable on the occurrence of PH while controlling for each other independent variable.

From each Early Medieval cremation deposit, if available, an otic capsule (of the *pars petrosa ossis temporalis*; $n = 9$), a diaphysis ($n = 64$), and a rib fragment ($n = 40$) were sampled. Diaphysis ($n = 2$) and rib ($n = 1$) samples were taken from the Iron Age cremation deposits. Unfortunately, no suitable dentine or dental enamel were available for analysis. The tooth root fragments that were retrieved were either too small to identify or not sufficiently calcined. For comparison, four samples were also taken from calcined pig diaphyses (Nieweg 2018) that accompanied the cremated human remains. Only fully calcined bone was sampled to ensure that the $^{87}Sr/^{86}Sr$ obtained represent the endogenous ratios (Snoeck et al. 2015; McMillan et al. 2019)

Cremated bone fragments of the ribs and diaphyses (c. 50 mg) were mechanically cleaned by removing the outer surface with a diamond-tipped burr after which they were rinsed three times with MilliQ water. For each rinse, the samples were placed for 10 min in an ultrasonication bath. Cremated bone fragments were then treated with 1M acetic acid for 3 to 10 min in the ultrasonication bath, rinsed again three times with MilliQ water, and 10 min ultrasonication (Snoeck et al. 2015). The otic capsule of the pars petrosa was sampled following Veselka et al. (2021). This method consists of exposing the various features of the otic capsule (i.e. the cochlea, vestibulum, and semicircular canals) via a midmodiolar cut of the pars petrosa. This enabled the optimal sampling of just the internal cortex (IC) of the otic capsule, allowing childhood ^{87}Sr/^{86}Sr to be obtained (see Veselka et al. 2021). The powdered IC sample underwent the same pre-treatment, but 0.1M acetic acid was used for only one min.

Strontium was extracted from the samples and purified following the protocol described in Snoeck et al. (2015) and measured on a Nu Plasma MC-ICP Mass Spectrometer (Nu015 from Nu instruments, Wrexham, UK) at the Université Libre de Bruxelles (ULB). During the course of this study, repeated measurements of the NBS987 standard yielded ^{87}Sr/^{86}Sr = 0.710246 ± 0.000045 (2SD for > 300 analyses), which is, for our purposed, sufficiently consistent with the mean value of 0.710252 ± 0.000013 (2SD for analyses) obtained by TIMS (thermal ionization mass spectrometry) instrumentation (Weis et al. 2006). All the sample measurements were normalized using a standard bracketing method with the recommended value of ^{87}Sr/^{86}Sr = 0.710248 (Weis et al. 2006). Procedural blanks were considered negligible (total Sr (V) of max 0.02 vs. 7–8V for analyses; i.e. ≈ 0.3%). For each sample, the ^{87}Sr/^{86}Sr is reported with a 2σ error (absolute error value of the individual sample analysis—internal error).

[Sr] in a fraction of the sample digests (see above) were diluted with 3% HNO_3, after which the [Sr] in the sample digests were measured using a Thermo Scientific Element 2 sector field ICP mass spectrometer in low (^{88}Sr) resolution using indium as an internal standard and external calibration vs. various reference materials (SRM1400, CCB01) at the Vrije Universiteit Brussel (VUB), Belgium. The actual [Sr] were calculated by normalizing the calcium data ([Ca]) to 40%. Accuracy was evaluated by the analysis of two internal bioapatite standards (ENF and CBA). Based on repeated digestion and measurements of these reference materials, the analytical precision of the applied procedure is estimated to be better than 5% (1SD, $n = 33$ for CBA and $n = 5$ for ENF).

The data on sex, age, and pathological anomalies were combined with ^{87}Sr/^{86}Sr and [Sr] analyses. A Shapiro-Wilk test was performed to evaluate if the ^{87}Sr/^{86}Sr and [Sr] of the diaphyses and ribs were normally distributed. For the variables that were not normally distributed, a Kolmogorov-Smirnov test was performed to assess if variables age, sex, and PH affected the distribution of ^{87}Sr/^{86}Sr and [Sr]. The two Iron Age cremation deposits were not considered in any of these tests. Statistical significance was set at $p < 0.05$.

To create a biologically available strontium (BASr) map of the surrounding regions, a total of 26 plant samples from nine distinct locations in the Netherlands and Belgium were collected in 2019 (L01-L03; Belgium and BV01-BV06; the Netherlands, Fig. 2). Samples were taken away from cities, villages, and roads to minimize the anthropogenic impact on the strontium isotope ratios of the plants. Where possible, grasses, shrubs, and trees were collected following the *plant sampling strategy* outlined in Snoeck et al. (2020B). Some nuts also were collected at BV02 and BV03. After being left to dry at room temperature, about 500 mg of plant material was placed in a Teflon vial. Samples were acid digested three times with an Anton Paar Multiware GO Plus microwave digestion system using the Organic B program, which consists of two 10-min phases at 100°C and 180°C, respectively, for a total duration of 40 min including warming steps. The first run was performed with 5ml HNO_3 14M, the second one adding 1ml HF 23M, and the third one adding 1ml H_2O_2. Once fully dissolved, the solution was transferred in a 7 ml Teflon beaker and left to dry at 100°C on a hotplate. Once dry, the strontium was extracted following the same procedure as for the cremated bones outlined above.

The BASr map of the Limburg region crossing the Netherlands, Belgium, and Germany (see Fig. 3) was constructed using the isotope package model developed for the Isle of Skye (Evans et al. 2009), later applied to the rest of Britain (Evans et al. 2010), and more recently to Ireland (Snoeck et al. 2020B). The high resolution global lithological map (GLiM v1.0), which was developed at the University of Hamburg from the assemblage of existing regional geological maps translated into lithological information with the help of regional literature (Hartmann and Moosdorf 2012), was used as a geological base map to develop the BASr map of the studied area. According to the GLiM map, different types of carbonate sedimentary rocks, siliciclastic sedimentary rocks, unconsolidated sediments, and mixed sedimentary rocks characterize the Limburg region (Fig. 2).

For each of the nine sampled locations, a median ^{87}Sr/^{86}Sr was calculated using the measured values from grass, shrub, nut, and tree samples. Median values of georeferenced sampled spots were assigned to the corresponding polygons (outcrops) of the vector GLiM map using the *Spatial Join* tool in ArcGis 10.3.1. This geoprocessing tool is used to join the attributes from one feature (i.e. the data points corresponding to the measured ^{87}Sr/^{86}Sr medians at the sampled locations) to another feature (i.e. the bedrock map) based on their spatial relationship. The ^{87}Sr/^{86}Sr medians were calculated for non-sampled outcrops of sampled bedrock formations based on the measured values of the sampled outcrops. These values were

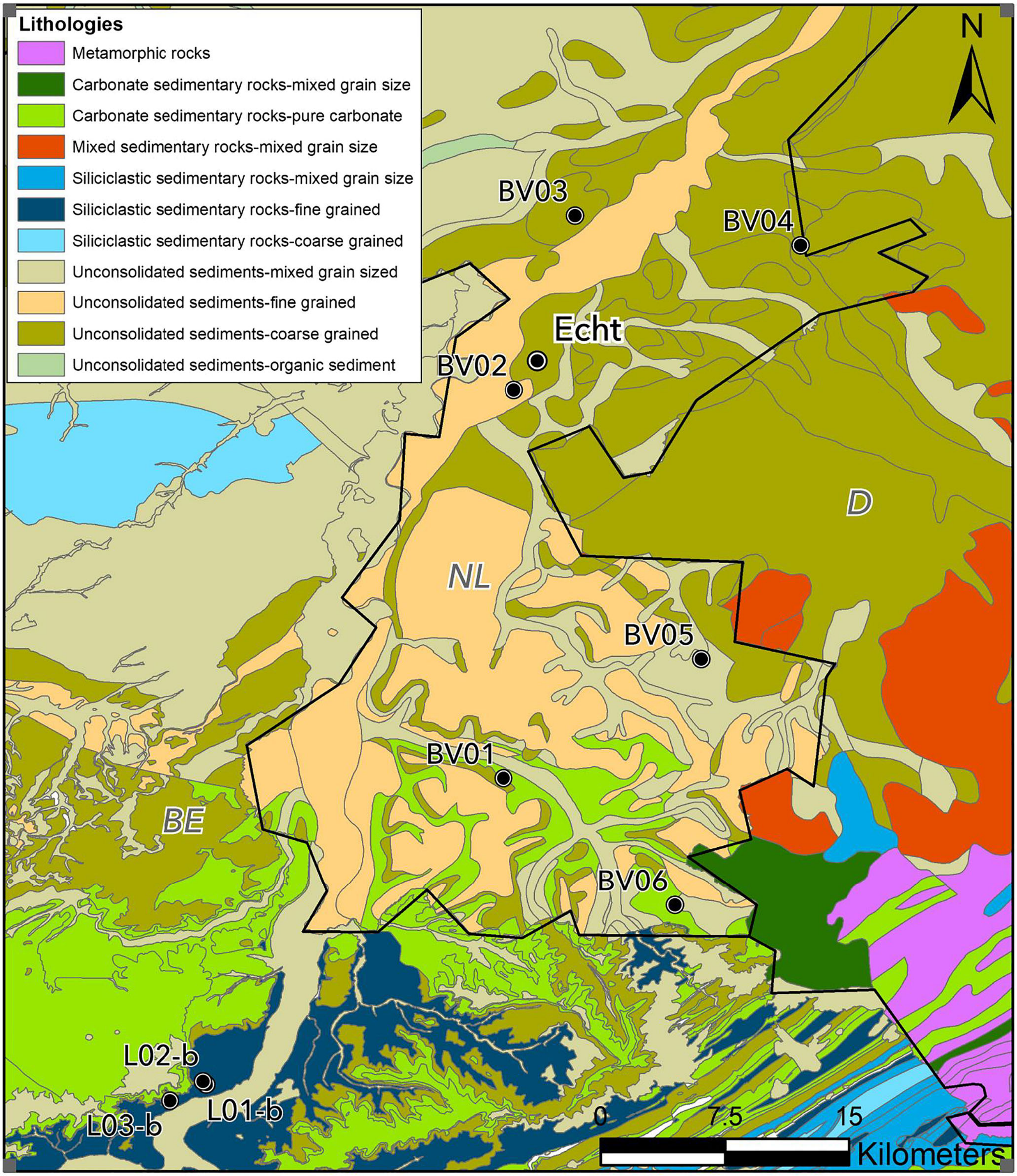


Fig. 2 Geological map of Echt and its surroundings (based on the global GLiM map by Hartmann and Moosdorf 2012)

assigned to the outcrops of four different geological formations, combining measured ^{87}Sr/^{86}Sr of samples BV01/L03-b, BV03/BV04, BV05/BV06, and L01-b/L02-b. Sample BV02 represents a fifth geological formation, which was sampled only once. Geological formations for which no samples are available were left in white in the BASr map. The corresponding error map provides an estimate of the variation in the isotopic ratios showing the median absolute deviation (MAD), which was calculated using the median of the absolute

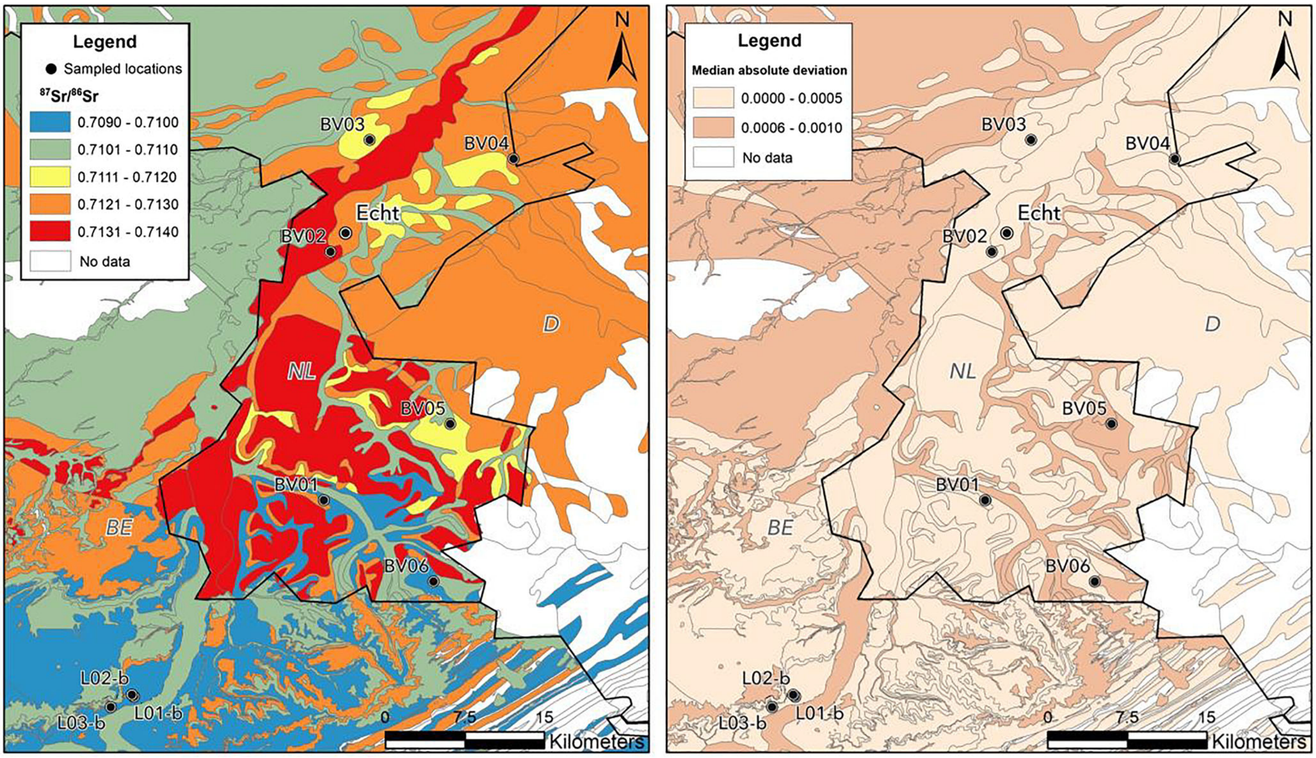


Fig. 3 Bioavailable strontium of Echt and its surroundings: (right) median strontium isotope ratio and (left) median absolute deviation (MAD)

difference between the $^{87}Sr/^{86}Sr$ of each plant sample and the median for the outcrop/formation it is located on.

Complementary to the typological dating, radiocarbon dating on 19 carefully selected fragments of calcined human bone and 15 fragments of calcined animal bone was carried out at the Royal Institute for Cultural Heritage, Brussels (KIK-IRPA). Only fully calcined (white) pieces of cremated bone were chosen. The procedure was composed of three different steps: pre-treatment, CO_2 extraction and graphitization, and measurement by accelerated mass spectrometry (AMS) (Van Strydonck et al. 2005, 2009). Firstly, the applied pre-treatment protocol started with the removal of the bone surface, which is less protected against C substitution, by acid treatment with hydrochloric acid (HCl, 8%) until ca. 50% of the material was leached. The samples were then washed several times with MilliQ water, dried in the oven, ground, and left in acetic acid (CH_3COOH, 1%) for 24h to remove secondary carbonates. Afterwards, the bone powder was rinsed with MilliQ water and dried again in the oven (Wojcieszak et al. 2020). Secondly, reaction was done under vacuum with phosphoric acid (H_3PO_4, 85%), and the released CO_2 was captured in a reactor and combusted with Ag and CuO. The CO_2 was then cryogenically trapped and converted to graphite at 680°C using pre-treated Fe (Alfa Aesar, iron powder, spherical, <10 μm, 99.9%) as catalyst. Lastly, the $^{14}C/^{12}C$ ratio in the graphite was AMS measured and converted into a radiocarbon age (expressed in years BP), after correction for isotope fractionation, using the $\delta^{13}C$ AMS measurement. All the measurements were obtained with the AMS type MICADAS, mini carbon dating system, at the KIK-IRPA (Lab-code: RICH) (Boudin et al. 2015). Calibration of the radiocarbon ages (BP) into calendar years (BC/AD) was performed using the software OxCal 4.4 (Bronk Ramsey 2009) and the atmospheric calibration curve IntCal20 (Reimer et al. 2020).

Results

Typological dating of the urns from M11S100 and M78S250 suggested these deposits to be from the Iron Age (Verhoeven 2015). M11S100 yielded a radiocarbon date between 776 and 542 BC for the 2σ probability (RICH-27476), and M78S250 had a date between 768 and 422 BC for the 2σ probability (RICH-29346), both clearly belonging to the Early Iron Age, confirming and refining the initial date based on pottery typology. The $^{87}Sr/^{86}Sr$ of the diaphyseal fragment from M11S100 was 0.7135 and the [Sr] was 68 ppm, while of the $^{87}Sr/^{86}Sr$ of the rib 0.7131 and [Sr] was 85 ppm. For M78S250, no rib fragment was available, and the $^{87}Sr/^{86}Sr$ of the diaphyseal fragment was 0.7137 and [Sr] was 94 ppm.

In the 73 Early Medieval cremation deposits, a total of 78 individuals were identified as five cremation deposits contained at least two individuals based on the osteoarchaeological analyses (Veselka 2017; SI 4). Of the 78 identified individuals, 12 were nonadults, 43 were adults, and

23 could not be identified (Veselka 2017; SI 2). All the radiocarbon dates (SI 5) suggested a continuous use of the cemetery and confirm the cremation deposits to be from the fifth to sixth centuries, with the oldest date ranging from 415 to 538 AD (RICH-27445) and the youngest date ranging from 551 to 640 AD (RICH-27456) both for the 2σ probability.

The plant samples collected to characterize the BASr map around Echt have ^{87}Sr/^{86}Sr ranging from 0.7088 to 0.7141 (SI 6) with the highest values observed on fine-grained unconsolidated sediments along the course of the Meuse river and western territories in the Netherlands (BV02-BV05). The lowest values correspond to the fine-grained siliciclastic sedimentary rocks in the area of Liège in Belgium and on pure carbonate sedimentary rocks in southern Dutch Limburg (BV01, BV06; L01-L03). The first attempt at creating a BASr map of Echt and its surroundings shows large isotopic variations with higher ^{87}Sr/^{86}Sr (up to 0.7140) located in the northern and central parts, while the southern areas are defined by lower values (below 0.7110; Fig. 3).

The ^{87}Sr/^{86}Sr of the cremated human remains vary markedly with values ranging from 0.7096 to 0.7139 (± 1SD), and also the [Sr] show a relatively large range from 57 to 331 ppm (Fig. 4; Table 1; SI 7). While highly variable, all ^{87}Sr/^{86}Sr fall within the range seen in plants from the surrounding region (0.7088–0.7141). The majority of skeletal elements have strontium isotope ratios that are within the yellow and orange area (Figs. 3 and 4), which are within a 10–15 km radius from Echt. Three diaphyseal samples and one rib sample had ^{87}Sr/^{86}Sr that correspond to the blue area, which is farther away from Echt (≥ 40 km). The mean of ^{87}Sr/^{86}Sr is slightly lower in diaphysis compared to ribs and IC (Fig. 5). The highest mean of ^{87}Sr/^{86}Sr was observed in the calcined pig samples (SI 8).

When comparing the ^{87}Sr/^{86}Sr of individuals that had the IC, diaphysis, and rib available for sampling (Table 1; Fig. 6), several patterns can be observed. In pattern 1, there is a marked difference between the ^{87}Sr/^{86}Sr (Δ^{87}Sr/^{86}Sr) of the IC and the diaphysis (> 0.0009). The ^{87}Sr/^{86}Sr of the ribs show much less difference with the ratios of the IC, ranging from 0.0002 to 0.0008. The samples from cremation deposits M14S102, M16S107, and M27S094 show relatively large Δ^{87}Sr/^{86}Sr between the IC and the diaphysis (> 0.0005), with similar differences between the IC and the ribs suggesting hardly any difference between the diaphysis and rib samples (pattern 2). In the last pattern (pattern 3), relatively large differences between the strontium isotope ratios of the IC samples and the diaphysis can be observed, whereby either the ^{87}Sr/^{86}Sr of the diaphyses are higher or lower than the ^{87}Sr/^{86}Sr of the IC (≥ 0.0004). This difference is even larger between the IC and the ribs (> 0.0007).

The osteoarchaeological analyses reveal that a third of the individuals (with cranial fragments) presented porotic hyperostosis (Veselka 2017). Logistic regression analysis demonstrated that age (nonadult vs. adult), sex (female vs. male), and the occurrence of new periosteal bone formation on the lower limbs (present vs. absent) were not statistically significant predictors of porotic hyperostosis (Table 2). The Shapiro-Wilk tests yielded a normal distribution for strontium isotope ratios in diaphyses and ribs, while the distribution of [Sr] in diaphyses and ribs was not normally distributed (p = 0.017 and p = 0.003, respectively; SI 9). In Table 3, the results of the Kolmogorov-Smirnov tests are provided that evaluated the difference in ^{87}Sr/^{86}Sr and [Sr] of the diaphyseal and rib fragments between nonadults and adults, females and males, and individuals affected by porotic hyperostosis and those not affected. However, none of the differences between ^{87}Sr/^{86}Sr and [Sr] were statistically significant for the age (nonadults vs. adults), sex (female vs. male), or porotic hyperostosis (present vs. absent) comparisons.

Discussion

The presence of Iron Age pottery and Iron Age cremation deposits M11S100 and M78S250 point to the cemetery of

Table 1 ^{87}Sr/^{86}Sr and [Sr] in the internal cortex of the otic capsule (IC), diaphysis (D), and rib (R) per cremation deposit

Cremation	^{87}Sr/^{86}Sr IC	2σ	[Sr] (ppm)	^{87}Sr/^{86}Sr D	2σ	[Sr] (ppm)	^{87}Sr/^{86}Sr R	2σ	[Sr] (ppm)
M06S097	0.711787	0.000009	100	0.712209	0.000010	119	0.712572	0.000017	149
M08S087	0.712744	0.000010	62	0.711406	0.000009	75	0.711099	0.000009	69
M14S102	0.712113	0.000008	102	0.709944	0.000011	161	0.709746	0.000011	231
M16S107	0.711116	0.000012	119	0.710407	0.000010	103	0.710439	0.000008	108
M19S106	0.713931	0.000011	139	0.713089	0.000010	95	0.712385	0.000008	97
M27S094	0.712492	0.000009	102	0.711893	0.000006	158	0.711587	0.000009	166
M36S121	0.712625	0.000010	72	0.710982	0.000011	88	0.711774	0.000009	56
M49S129	0.711882	0.000008	131	0.711020	0.000010	167	0.711673	0.000014	140
M57S125	0.710537	0.000007	128	0.711159	0.000008	144	0.712047	0.000010	196

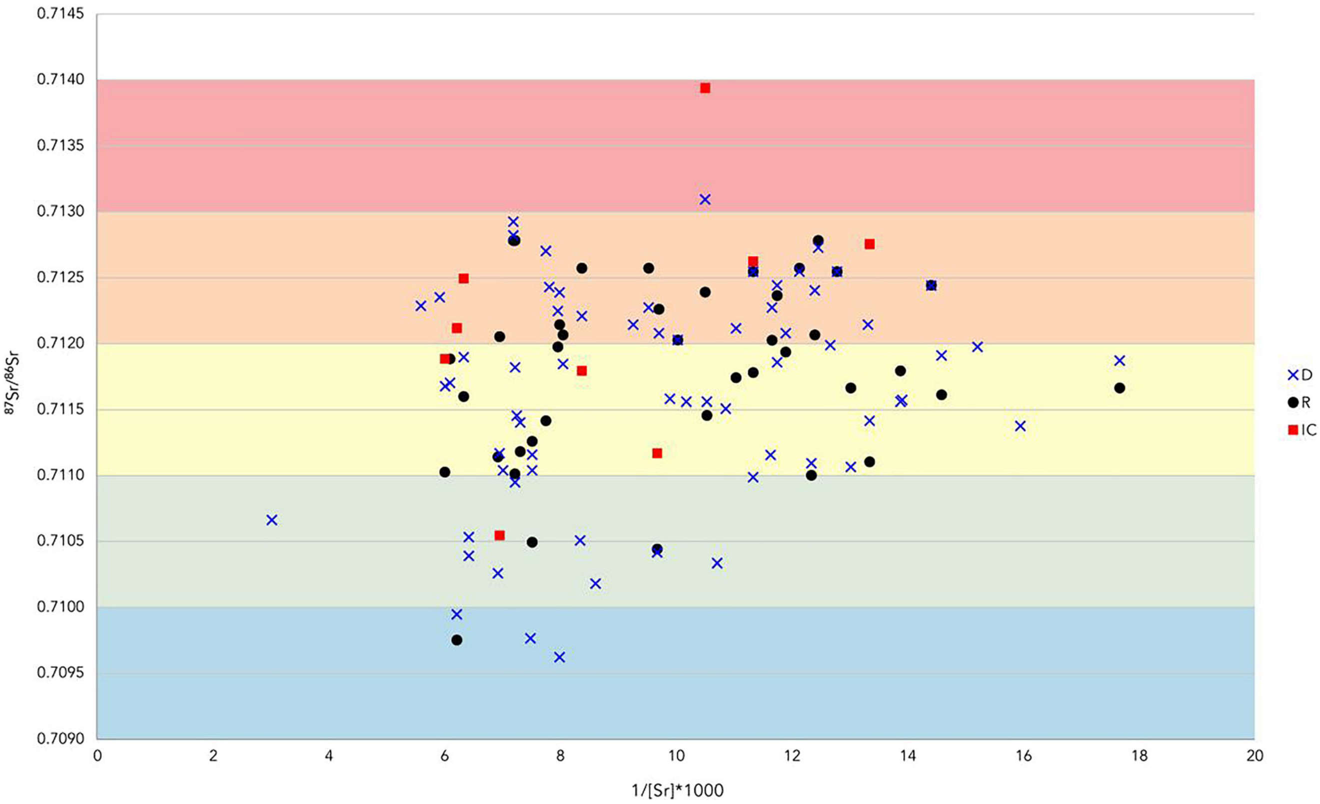
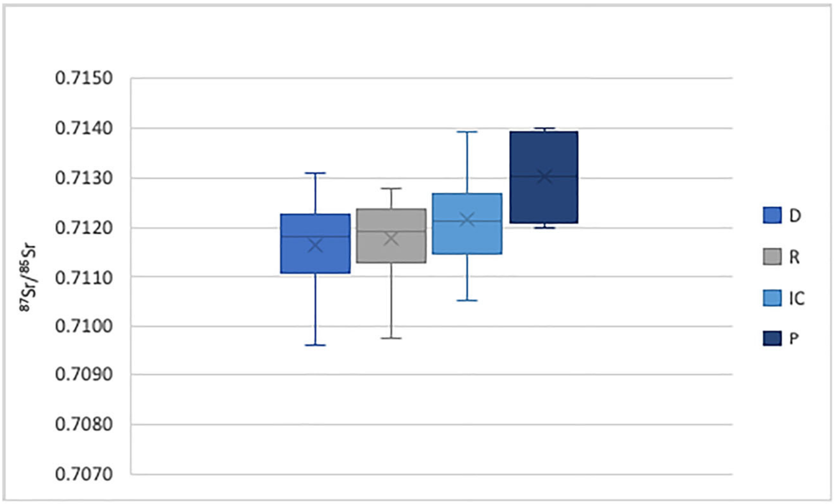


Fig. 4 Strontium isotope ratios ($^{87}Sr/^{86}Sr$) vs. Sr concentrations (expressed as 1/[Sr]*1000) per skeletal element. D, diaphysis; R, rib; IC, internal cortex of the otic capsule of the pars petrosa; the colours in the graph correspond to the colours on the BASr map (see Fig. 3

Echt being established by an Early Medieval burial community in an area that already had traces of earlier use, habitation, and/or special significance (Theuws 1998; Tys 2018). This is commonly observed in Early Medieval cemeteries, as was the case in the surrounding cemeteries of Sittard, Obbicht, Stein (Kars et al. 2016), Ophoven (Roosens 1976), Maasmechelen (Steenhoudt and Smeets 2018), Stokkem (De Winter and Wesemael 2014), and Posterholt (De Haas and Theuws 2013), and the more remote cemeteries of Bergeijk (Theuws and Van Haperen 2012), Alphen (Verhoeven and Janssen 2019), Uden (Knippenberg and Theuws 2019), Wijchen (Heeren and Hazenberg 2010), Lutlommel (Van Bostraeten 1965), and Rosmeer (Roosens et al. 1976).

The significance of the cemetery location would contribute to the establishment and development of the identity of the burial community (Theuws 1998; Tys 2018) and would have been defined by various characteristics, such as burial rite. Inhumation was reported to have been practiced more

Fig. 5 Boxplots of $^{87}Sr/^{86}Sr$ per skeletal element. D, diaphysis; R, rib; IC, internal cortex of the otic capsule of the pars petrosa; P, pig diaphysis



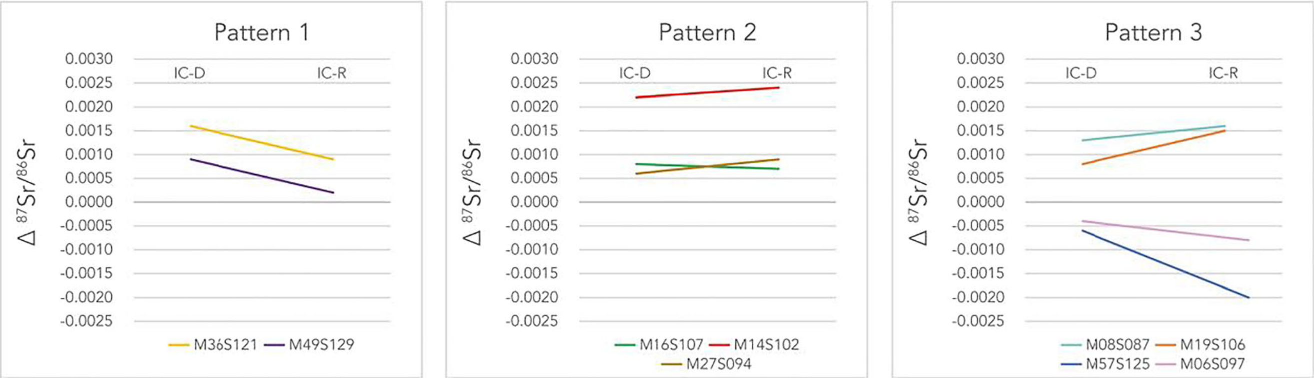


Fig. 6 Observed patterns in $\Delta^{87}Sr/^{86}Sr$ between inner cortex of the otic capsule in the pars petrosa (IC), the diaphysis (D), and the rib (R)

frequently from the Late Roman period (fourth century AD) onwards and is expected to have been the dominating burial rite in the fifth to seventh centuries (Tichelman 2013). This is clearly observed in the Early Medieval cemeteries of Alphen, Bergeijk, Uden, Posterholt, Rosmeer, Sittard, Obbicht, Ophoven, Lutlommel, Maasmechelen, Stokkem, and Stein, whereby the dominant (or exclusive) funerary practice was inhumation (Verhoeven and Janssen 2019; Theuws and Van Haperen 2012; Roosens 1976; Steenhoudt and Smeets 2018; De Winter and Wesemael 2014; Knippenberg and Theuws 2019; Kars et al. 2016; Theuws 2013; SI 1). In the cemetery of Wijchen, a larger number of cremation deposits were observed (n = 36), yet, the number of inhumation graves (n = 309) is still markedly larger (Heeren and Hazenberg 2010). The cremation deposits were contemporaneous with the inhumations in all these cemeteries, although, in Wijchen, the cremation deposits were dated to the fourth to fifth centuries, while the inhumation graves showed a partial overlap by dating to the fifth to seventh centuries (Heeren and Hazenberg 2010). In the cemetery of Echt, a temporal and somewhat spatial dichotomy can be observed, whereby the majority of the fifth- to sixth-century cremations (72 out of 73) were more or less clustered in the centre, while the seventh-century inhumation graves were located in the periphery (see Verhoeven 2015). Why was the dominant burial practice cremation in the cemetery of Echt, if the other contemporaneous cemeteries practiced inhumation?

In the fourth century, written sources suggested that large parts of the countryside were abandoned and subsequently repopulated by immigrants in the late fourth and early fifth centuries (Heeren 2017; Theuws 2008). These settlers were coming from elsewhere occupying the countryside, introducing their possibly divergent sociocultural practices to the new area, visible as a rapid change in material cultural, building styles, and burial practice (Heeren 2017). It is possible that the Echt cemetery was originally founded by such settlers, who practiced cremation rather than inhumation, as opposed to the other cemeteries, potentially coming from regions where cremation was still the dominant burial rite. The families that were part of the burial community of Echt would have expanded over time (e.g. via marriages with individuals from neighbouring farmsteads) while keeping cremation as the main burial rite, resulting in a markedly higher number of cremations in the Echt cemetery compared to the other regional cemeteries (Fig. 1; SI 1). Since the inhumations were preserved in situ, dating of the graves was based on grave shape and grave good typology, suggesting that it is possible that some of the inhumation graves actually may have been from the sixth century. If this was the case, an intermediate area within the cemetery of Echt would likely exist, whereby inhumation and cremation graves would occur together. However, the almost strict difference in spatial distribution between inhumation and cremation graves and the lack of an intermediate area (Verhoeven 2015) makes it unlikely to state

Table 2 Logistic regression analysis results of porotic hyperostosis with independent variables age, sex, and new periosteal bone formation on the lower limbs

Independent variable	*B*	SE	Wald	*p*-value	Odds ratio	95% coincidence interval	
						Lower	Upper
Age	0.118	0.424	0.078	0.781	1.125	0.490	2.586
Sex	1.035	0.987	1.099	0.294	2.816	0.407	19.506
NPBF	1.233	0.997	1.531	0.216	3.433	0.487	24.208
Constant	−4.040	3.625	1.243	0.265	0.018		

Age (nonadults coded 1 and adults coded 2), sex (females coded 1 and males coded 2), new periosteal bone formation on the lower limbs (NPBF; present coded 1 and absent coded 2)

Table 3 Statistical assessment of the differences in $^{87}Sr/^{86}Sr$ and [Sr] of the diaphyseal and rib fragments between nonadults and adults, females and males, and individuals with or without porotic hyperostosis

	Kolmogorov-Smirnov *Z*	*p*-value
Nonadults vs. adults		
$^{87}Sr/^{86}Sr$ D	0.876	0.427
$^{87}Sr/^{86}Sr$ R	0.844	0.475
[Sr] D	*1.373*	*0.046*
[Sr] R	1.322	0.061
Female vs. male		
$^{87}Sr/^{86}Sr$ D	0.500	0.964
$^{87}Sr/^{86}Sr$ R	0.770	0.593
[Sr] D	0.750	0.627
[Sr] R	1.027	0.242
PH present vs. absent		
$^{87}Sr/^{86}Sr$ D	1.108	0.172
$^{87}Sr/^{86}Sr$ R	0.691	0.727
[Sr] D	1.084	0.190
[Sr] R	1.309	0.065

D diaphysis, *R* rib, *PH* porotic hyperostosis

Statistically significant results are displayed in italic

inhumation and cremation were practiced simultaneously, contrasting many other Medieval cemeteries that practiced both rites for longer periods of time (Lippok 2020). Based on this spatial and temporal dichotomy of both types of graves, the initial burial community of Echt, that practiced cremation in the fifth and sixth centuries, did not abruptly change their burial rite in the seventh century to inhumation. Rather, it is suggested that a subsequent burial community replaced the dominant burial rite of cremation with inhumation, conforming to the burial practice of the surrounding cemeteries.

The landholdings and farmsteads that were used by the Echt families were probably dispersed over the entire region of the Middle Meuse Valley. This valley is characterized by its topographical variety (hills, alluvial plains, and more) and differential geological substrates (see Fig. 2). This explains the wide range of $^{87}Sr/^{86}Sr$ in the Echt individuals, which most likely is related to the geological complexity of the area and the marked variations seen in the $^{87}Sr/^{86}Sr$ of the plants (see Fig. 3). The vast portion of the foods consumed would have originated from the area directly surrounding the farmstead and little homogeneity in $^{87}Sr/^{86}Sr$ is to be expected from the human remains in an area with such variation in BASr. Although no farms were identified nor excavated in the Meuse Valley, other areas in the Netherlands and Belgium demonstrated the fields to be located directly next to the farms (Dijkstra 2011; Theuws 2011; Ervynck et al. in press), suggesting that it is likely this was also the case for the Meuse Valley. Only three cremation deposits (M14S102, M37S114, and M45S113) yielded $^{87}Sr/^{86}Sr$ that correspond to areas located at a distance of at least 40 km (blue area Fig. 3) from Echt, whereas the rest of the $^{87}Sr/^{86}Sr$ fall within areas that are much closer (~ 10–15 km radius). This may suggest that these remains belonged to individuals that died shortly after their arrival in farmsteads closer to Echt, whereby the $^{87}Sr/^{86}Sr$ would still represent their former geographical origin. Another possibility is that some individuals lived further away, yet, needed or wanted to be buried at Echt cemetery, maybe as it still practiced cremation, although other cemeteries (e.g. Stein—exclusively inhumations) would have been much closer. The relatively low weights of cremation deposits M37S114 and M45S113 (4.9 g and 6.7 g, respectively; Veselka 2017) despite their relatively large burial pits (Verhoeven 2015) would have facilitated the transport of the remains but may also suggest that the larger part of the remains could have been buried in a cemetery closer to home and only a token deposit was brought to Echt. Although it is not entirely clear, it is likely to suggest that these individuals shared the same group identity and/or were part of the same burial community as the other individuals buried at Echt and therefore wanted to be (partially) interred at the same cemetery, where cremation was practiced rather than inhumation.

Only one Early Medieval cremation deposit (M19S16) yielded $^{87}Sr/^{86}Sr$ ($IC = 0.7139$; $D = 0.7131$) that correspond to the red area (Figs. 3 and 4; Table 1; SI 4; SI 6). Interestingly, the Iron Age cremation deposits also have high $^{87}Sr/^{86}Sr$ (0.7137 and 0.7135), suggesting that resources with high $^{87}Sr/^{86}Sr$ were indeed available in the area (as also evidenced by the BASr map), but for some reason, it was not consumed in significant amounts by those buried in Echt, resulting in only one Early Medieval individual with such high $^{87}Sr/^{86}Sr$. Alternatively, another explanation for the lack of high values corresponding to the “red” areas in human remains might be linked to a mixing of resources. The high ratios seen in the pig remains, going from 0.7120 to 0.7140, might further point in this direction. While only four specimens were analysed (SI 8), the fact they all have $^{87}Sr/^{86}Sr \geq 0.7120$ could suggest pig farming might have been localized to the orange and red areas. Still, meat has much lower [Sr] compared to crops (Montgomery 2010) and will only have a limited impact on the $^{87}Sr/^{86}Sr$ measured in human remains.

Despite the large variability in $^{87}Sr/^{86}Sr$, most individuals from Echt (74 out of 78) most likely consumed foods that originated from the geological areas from and close to Echt (see Figs. 3 and 4). Considering the limited differences between the $^{87}Sr/^{86}Sr$ of the diaphyses and the ribs (Fig. 5), regardless of turnover rate, long-distance mobility most likely was limited and little change occurred in the geological origin of the foods consumed over the course of an individual’s adult life, which would make the Echt inhabitants heavily dependent on the yield of their harvests. Bakels (2009) reported a decrease in agricultural production capacity in the south of the

Netherlands between the fifth and seventh centuries, and deteriorating climatic conditions during this time (Büntgen et al. 2016) are suggested to have resulted in crop failures and to have influenced other factors linked to the availability of foods in the various geological areas. This may have led to a marked decrease of foods resulting in a nutritionally inadequate diet, which may have contributed to the relatively high prevalence of PH in the individuals of Echt.

A third of the individuals buried at the cemetery of Echt displayed this lesion (Veselka 2017). Logistic regression analysis demonstrated that none of the independent variables (i.e. age, sex, and new periosteal bone formation) were a statistically significant predictor of PH. Furthermore, the differences between the ^{87}Sr/^{86}Sr in affected vs. unaffected individuals were not statistically significant. [Sr] in the rib fragments of affected individuals were higher, but this difference failed to reach statistical significance (p = 0.065). This implies that regardless of the geological area and type of foods consumed, the Echt individuals experienced a similar risk of developing PH. Although the exact aetiology of this lesion cannot be determined, the most common causes are deficiencies in vitamins C and D, and acquired anaemia, whereby the latter may result from iron deficiency or general malnutrition (Brickley et al. 2020). The possibility exists that nutritionally inadequate diets resulting from a decreased availability of foods increased PH prevalence in the Echt individuals. However, more research on the prevalence of PH in other Early Medieval cemeteries from the Meuse Valley is needed to better understand the possible relationship between PH formation and food availability as well as exploring other causes of PH, such as vitamin D deficiency, in the Early Medieval populations.

Contrasting the small differences in ^{87}Sr/^{86}Sr between the diaphysis and rib, relatively large differences in ^{87}Sr/^{86}Sr exist between the samples from the IC and the diaphyses and ribs (Fig. 6). For cremation deposits M06S097, M27S094, and M49S129, the osteoarchaeological analysis demonstrated that the remains of at least two individuals were buried together. It is possible that sampling more than one individual may (partially) explain the relatively large difference in ^{87}Sr/^{86}Sr between the IC and the other samples. Although osteoarchaeological analysis observed a most likely number of individuals of one for the other cremation deposits, the possibility exists that the remains of more than one individual were included. However, all individuals that had a pars petrosa available for strontium isotope analysis show an absolute difference in ^{87}Sr/^{86}Sr of at least 0.0004 between the IC and the diaphysis and ≥ 0.0007 between the IC and the rib. Therefore, it is likely to assume that also other factors are at play (see Veselka et al. 2021 for more details).

Instead, a relatively large difference between the ^{87}Sr/^{86}Sr of the IC and the diaphysis and/or rib suggests a marked shift in the origins of the foods that was consumed later in life, since the ^{87}Sr/^{86}Sr of the IC result from the food consumption in the first 2 years of an individual's life (Veselka et al. 2021) and the ^{87}Sr/^{86}Sr of the diaphysis and ribs is assumed to represent foods consumed closer to the time of death (Dupras and Schwarcz 2001; Prowse et al. 2005; Turner et al. 2009). It is possible that foods consumed by nonadults differed from the adult diet. However, the ^{87}Sr/^{86}Sr of the diaphyses and ribs were normally distributed. Since the difference in ^{87}Sr/^{86}Sr between IC and diaphysis and/or rib in nonadults is assumed to be small due to the limited time that has passed, age does not seem to have been the main contributing factor. Another possibility is that the relatively large differences between the childhood ^{87}Sr/^{86}Sr and those of the diaphyses or ribs were caused by mobility, characterizing inter-farmstead relationships, whereby individuals moved to geologically different areas later in life and thus consumed foods with a different ^{87}Sr/^{86}Sr.

The mean [Sr] in the diaphyses (91 ppm) and ribs (95 ppm) of nonadults were lower than those in adults (mean [Sr]D = 108 ppm; mean [Sr]R = 117 ppm). The uptake of calcium, and thus also strontium (Coelho et al. 2017), is influenced by a number of factors, such as age (Underwood 1977). During periods of rapid growth, the absorption of calcium is elevated (Brickley et al. 2020), and prioritizing calcium over strontium uptake may result in lower [Sr] (Lahtinen et al. 2021). This may (partially) explain why [Sr] are lower in nonadults than in adults. Although the difference in [Sr] between the diaphyses of nonadults and adults was statistically significant (p = 0.046), the difference in the [Sr] in nonadult vs. adult rib samples failed to meet statistical significance (p = 0.061) and more research on the possible influence of age and growth on differences in [Sr] between nonadults and adults is needed.

Our study demonstrates that the large-scale application of ^{87}Sr/^{86}Sr and [Sr] analyses aids in the reconstruction of landscape use and mobility in the Meuse Valley and helps us to better understand living conditions in the Early Medieval period by jointly evaluating PH prevalence and ^{87}Sr/^{86}Sr and [Sr]. In particular it showed that the large variability in ^{87}Sr/^{86}Sr did not connote mobility, but rather supported the notion of localized farming. Depending heavily on the yield of the local harvests, decreasing agricultural capacities of the soil and unfavourable climatic conditions would have severely impacted this yield, possibly leading to decreasing food supplies, partially explaining the relatively high number of individuals with PH. Despite being dispersed over the landscape and in some cases being more than 40 km away from Echt, the cemetery served as a central place that shaped the burial community, consisting of individuals and/or families that practiced a divergent burial rite compared to the other surrounding Early Medieval cemeteries.

While clearly demonstrating the potential of multi-proxy analyses on cremated human remains, this work points towards different issues that need to be considered when interpreting such results. If the Echt ^{87}Sr/^{86}Sr were compared to the $^{87}Sr/^{86}Sr$ of this area in the isoscape of Kootker et al. (2016), the majority of Echt individuals would have consumed foods not originating from surrounding areas, suggesting large-scale mobility. However, the reported $^{87}Sr/^{86}Sr$ ranging from 0.70857 to 0.70795 was based on a limited number of samples ($n = 2$), whereby no sample was obtained in the immediate vicinity of Echt (Kootker et al. 2016). This stresses the need of a more refined BASr map, as demonstrated in this paper (Fig. 3), to improve our understanding of landscape use and mobility patterns. The relationship between [Sr] in bone, age, and bone turnover rates in various skeletal elements is complex and influenced by an interplay of several factors, such serum vitamin D levels, affecting calcium and strontium uptake during life (Coelho et al. 2017; Underwood 1977; Brickley et al. 2020). More research is needed to improve our understanding of the influence of bone turnover rates, metabolic bone diseases, and age on $^{87}Sr/^{86}Sr$ and [Sr]. Furthermore, our study has shown the usefulness of investigating $^{87}Sr/^{86}Sr$ in animal remains, and additional research of calcined animal remains may provide novel insights in farming and livestock production as diet.

Conclusion

A multi-faceted approach was applied to the Early Medieval cemetery of Echt by combining information on demography and paleopathological lesions with $^{87}Sr/^{86}Sr$ and [Sr] to better understand landscape use and mobility patterns in the Meuse Valley. As opposed to the other surrounding Early Medieval cemeteries, the cemetery of Echt yielded a remarkably high number of cremation deposits ($n = 73$) from the fifth to sixth centuries, while all the documented inhumations were dated to the seventh century (Verhoeven 2015). Cremation was posited to have been the main burial practice of the original settlers and additional families that founded the Early Medieval cemetery of Echt, as opposed to the other groups of individuals in the vicinity that practiced mainly inhumation. At the beginning of the seventh century, a consecutive burial community is postulated to have introduced the practice of inhumation, thereby discarding cremation as a burial rite.

$^{87}Sr/^{86}Sr$ and [Sr] demonstrated a large variability, matching the geological complexity of the area and supporting the idea of habitation in the form dispersed farmsteads, whereby the vast portion of the foods would have originated from the land directly surrounding the farmstead. This may have exposed the individuals to a higher risk of developing PH, since unfavourable living conditions, such as deteriorating climatic circumstances and decreasing agricultural production capacity of the area, would have markedly affected the availability of foods and may have led to vitamins C and D deficiencies or general malnutrition in Echt and/or large parts of its surroundings.

The relatively small difference in $^{87}Sr/^{86}Sr$ of the human diaphyses and ribs and the slightly larger difference in $^{87}Sr/^{86}Sr$ of the pig diaphyses suggest little variation in food types existed during life and long-distance mobility was unlikely, but more research on calcined animal bones is needed to increase our understanding of animal diet in the Early Medieval period. The relatively large differences between childhood and adulthood $^{87}Sr/^{86}Sr$ may support the idea that regional mobility existed as a result of inter-farmstead relationships, whereby individuals would move to geologically different locations later in life, but still in the vicinity of the central cemetery.

This study has demonstrated the value of a multi-faceted approach to the rather unique cemetery of Echt. The combination of several types of data significantly improved our understanding of burial communities in the Early Medieval period and enhanced our knowledge of identity expression, health, landscape use, and mobility in the Meuse Valley.

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Availability of data and material Full data set is available in the paper (main text and as supplementary information) and will be shared in the online database IsoArch (Salesse et al. 2018).

Code availability Not applicable

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Declarations

Competing interests The authors declare no competing interests.

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