

Staying within the boundaries: Substantial local mobility in mid-3rd millennium Southern Scandinavia revealed by laser ablation Sr isotope analysis

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Abstract

As far as culture groups go, the Corded Ware Culture (CWC, c. 2900-2200 BCE) is understood as the epitome of migration, pastoralism and long-range movement. This article reports on a different and prevailing mode of mobility observed in the Battle Axe Culture (BAC), a conspicuous late CWC variant residing in southern Sweden. Based on teeth from 70 skeletons, the reported result describes the mobility level from c. 2600 BCE (when the BAC first appeared) until c. 2200 BCE (when the BAC transformed into a Late Neolithic (LN) culture).

The skeletal data derives from burials in flat grave cemeteries (Sweden) as well as megalithic passage graves (from Denmark and Sweden). The hitherto predominant 'bulk strontium isotope method' is capable of distinguishing between absent movement (locals) and substantial movement (non-locals). Here, we rely on spatially-resolved, geographically and culturally linked tooth data generated by the laser-ablation-Sr-isotope method, which endorses detailed insight into individuals' movements over several years in childhood and adolescence.

This biographical result demonstrates that most people regularly travelled short distances throughout their lifetimes while also staying within the neighbourhood of their place of burial and/or birth. Long and middle range movements were the exception. The present study yields new essential information regarding a significant difference found in the strontium isotope values between BAC and LN in the principal area of SW Scania. It unfolds a gradual development from a local-scale territorially defined pastoralism in the BAC towards a predominantly sedentary agricultural economy in the LN.

Keywords: Laser ablation; Strontium isotope analysis; Neolithic; Southern Scandinavia; Megaliths

Introduction

This study reports on a hitherto unknown mobility rhythm in the Nordic Corded Ware Complex (CWC) which is often interpreted in terms of large-scale migration and, implicitly, high general mobility. The principal analytical focus is the Swedish Battle Axe Culture (BAC) a regionalised late CWC variant residing in southern Sweden c. 2600-2200 BCE. Selected data from the Danish Single Grave culture (SGC-Zealand) has been added along with data from the earliest Late Neolithic (LN I). Human society commonly embraces interlocked modes of mobility adjusted to parameters such as societal stability, gender, technology, economy, tradition, continuity and change (cf. Urry 2007). In our case, the mobility system may especially conform to the economy whether that was pastoral, agricultural or a combination of the two. Different (and still vaguely understood demographic processes) characterised Scandinavia in the long CWC period. The SGC and the BAC both have deep CWC roots tracing back to the earliest third millennium BCE.

The 3rd millennium BCE context – current state of knowledge

Over the last decade, the tribal societies of the 3rd millennium BCE have received excessive scholarly attention stimulated by paleogenomic and strontium isotope results in combination addressing the question of the range and constitution of early human mobility. Several high-impact research articles have confirmed and particularised fundamental changes in the biocultural makeup of Scandinavian Middle-Neolithic tribal societies (Allentoft et al. 2015; 2024; Haak et al. 2015; Lipson et al. 2017; Frei et al. 2019; McColl et al. 2025). The current state of knowledge can be summarised as follows:

Firstly, migrations 2900-2800 BCE from the Pontic Steppes gave rise to the intrusion of a plethora of Corded Ware societies in Northern and Central Europe. The first and still enigmatic CWC arrived in Scandinavia around 2900 BCE in the earliest local Middle Neolithic B (MNB), a date which coincides with evidence for forest clearances and cultural shifts. Contemporary genomic data reveals a second near complete population turnover at around this time, too. Computations of genomic data suggest a marked dominance of people with 'Steppe Ancestry' over 'Farmers' represented by Funnel Beaker (FBC) and Globular Amphora (GAC) groups. Even at this early stage, there was seemingly limited biological mixing across groups. The material culture especially in southern and central Jutland and southern Sweden comprises the so-called Horizon A features of early Corded Ware pottery and early-type battle axes (Malmer 1962; 2002; Hübner 2005; Klassen 2005; Ebbesen 2006; Madsen 2020; Kristiansen 2022). The resident FBC 'Farmers' nonetheless continued to exist alongside CWC communities, thereby indicating some form of cohabitation (Brink 2009; Iversen 2016; Madsen 2020; 2024; cf. Klassen et al. 2020; Pilegaard-Justesen 2023).

Secondly, this early and very distinct historical turning point soon instigated demographic and regionally diverse developments; the mid-third millennium stands out clearly as the threshold to a new epoch of CWC expansion and diversification (e.g. Papac et al. 2021). Many Nordic CWC finds belong in this period (e.g. Hübner 2005; Brink 2009; Müller & Vandkilde 2021). Genetically, the Y chromosomal (male) haplogroup R1a reveals the firm presence of Steppe Ancestry (Allentoft et al. 2024; McColl et al. 2025). Female haplogroups in turn reveal 'Farmer' origins, denoting specific rules for intermarriage and, potentially, cases in which females may have travelled in from elsewhere (exogamy: e.g. Knipper et al. 2017; Massy et al. 2017; cf. Frei et al. 2019; Malmström et al. 2019; Egjford et al. 2021). By approximately 2600-2500 BCE, the CWC clearly had diverged into regional branches, eventually fading away with the rise of Bell Beaker cultures (BBC) or other Late Neolithic (LN) societies around 2200-2000 BCE (e.g. Brink 2009; Großmann 2016 cf. Papac et al. 2021) (Table I). A prominent regional CWC member is the Swedish BAC, which materialised as a cultural bricolage as it integrated features from the FBC, Continental CWC, Pitted Ware Culture (PWC), Continental BBC (from as early as 2500 BCE), and Forest Steppe. Genetically, the BAC has a less prominent Steppe signature (Skoglund et al. 2012; Malmström et al. 2015; Mitnik et al. 2018; Malmström et al. 2019), which fits the BAC signature of high cultural hybridity. This mixing of culture and genes seems to particularly characterize the period 2600-2200 BCE. Furthermore, the BAC may have practiced a mostly sedentary agropastoral economy scaffolded by robust population growth (Tornberg & Vandkilde 2025). This latter discovery may have implications for BAC and early LN mobility.

Thirdly, another more gradual development unfolded from c. 2300-2200 BCE, signifying the appearance of Late Neolithic culture. This was regularly influenced by Bell Beaker material culture, and, eventually, the full adoption of metallurgy c. 2000 BCE (Vandkilde 2017). The transition from CWC to the Late Neolithic emerged almost imperceptibly in terms of archaeological finds, and economy and society were deemed stable during the second half of the third millennium BCE (e.g. Brink 2009; Tornberg & Vandkilde 2025). The Y chromosomal (male) haplogroups now comprised R1b-L52, thereby confirming the continued distinct presence of Steppe Ancestry in the genomic data of the fading Middle Neolithic and emerging Late Neolithic (Allentoft et al. 2024).

The biocultural transformations and continuities described above call attention to the potential role of human mobility, hence prompting new questions. How was human mobility more precisely organized? Did mobility patterns vary over time, specifically from the CWC into the LN? Which societal constituents, such as gender/sex, economy and warfare, were possibly associated with or influential upon this mobility?

Period	Date BCE
CWC classical phase in Europe:	2900-2600
BAC and other regionalisations:	2600-2200
LN I and other early Late Neolithic phenomena:	2200-2000
Early Bronze Age in Europe:	2000-1600

Table 1. Chronological overview of the 3rd millennium BCE.

Searching for patterns of human mobility – recent methodological advances

As a social phenomenon, *human mobility* is reversibly imbedded in environment, society, culture and change and may even escalate the spread of epidemic diseases (Urry 2007; Seersholm et al. 2024). Patterns of mobility can change over time and may well correlate with, reflect or impact other societal components, such as sex/gender, war, technology, economy, food culture and even language (Kristiansen et al. 2017). Corded Ware groups are often highlighted as especially mobile due to their pastoral-like economy's subsistence on a mixture of plant and animal foods. Particularly women however emerge from the published data as highly mobile, likely due to kinship systems requiring female exogamy and involving different groups with differing economic strategies (Sjögren et al. 2016; Frei et al. 2019; Mitnik et al. 2019; Kristiansen 2022).

We here acknowledge the likelihood that different modes of mobility coexisted at the same or different tempo-spatial scales from the local to what was nearly global within the Copper Age rather than the long- and medium distance movements that are usually studied. We also consider it likely that time, continuity and change are critical factors, even if they are difficult to clearly pinpoint at present. Elevated mobility is a term that has so far mostly been bestowed upon certain individuals who were 'non-locals' travelling long-distance outside their home residences while other agents remained 'locals'. Recent studies, however, employ increasingly elaborate methods capable of revealing varying degrees of mobility, including gender-specific patterns, based on multi-proxy isotope evidence (e.g. Sjögren, Price and Kristiansen, 2016; Kristiansen et al. 2017; Massy et al. 2017; Mitnik et al. 2019; Ladegaard-Pedersen et al. 2021). While research is trending in this more nuanced direction, the division into locals and non-locals remains crudely one-dimensional. Previous isotope studies of SGC and BAC skeletal remains suggest only moderate mobility (Fornander 2015; Frei et al. 2019). Overall, however, 3rd millennium mobility is still quite poorly understood.

Analysis of strontium isotopes is now a standard bioarchaeological procedure to gain insight into past human and animal mobility. Traditionally, mobility studies are based on the average strontium ratio obtained by bulk dissolution of a piece of tooth enamel (e.g. Bentley 2006), which could be determined to be within or outside the boundaries of the bioavailable strontium signal of the place of burial when compared to strontium baseline data, i.e. an *isoscape*. The individual under study could, thus, be assessed as likely being either of local or non-local origin. In some cases, strontium values are inconclusive, e.g., the signals could be produced by living on liminal areas between significantly

diverging geologies, or, by moving (or regularly eating/drinking products) between two or more geologically distinct areas (Blank et al. 2018). The average values associated with bulk strontium isotope analysis are not sufficiently resolved to separate these kinds of scenarios.

Recent technological and methodological advances in strontium isotope analyses however allows higher resolution of mobility data through micro sampling with a laser ablation system coupled with a multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICPMS). This kind of micro sampling generates data from several sites over the tooth enamel instead of an average value of the complete sampled piece of enamel that is produced by bulk analyses. The data from laser ablation analyses can, thus, detect variations in strontium values between different measured sites of the enamel, informing about mobility over the complete timespan of enamel mineralization. For example, this allows for the detection of seasonal mobility and/or differences in strontium variations associated with sociocultural phenomena covering both short and long distances.

Material

A total of 903 Sr isotope spot measurements were conducted, 601 deriving from Scania (Sweden) and 302 from eastern Denmark. These measurements were obtained from 50 teeth coming from 45 individuals in Scania and 25 teeth from 25 individuals from Denmark. The Scanian sample was pooled from 15 different localities, primarily in NE and SW Scania where bone preservation is generally more favourable. The Scanian sites primarily consist primarily of BAC flat grave cemeteries or single flat graves (n=13), with additional remains from two passage graves: Carlshögen in SE Scania and Gillhög in NW Scania. Similarly, the Danish samples were collected from eight different passage graves, which have a generally good preservation of skeletal remains compared to flat grave cemeteries. These passage graves comprise Kyndeløse in N Zealand, Rævehøj and Borreby in W Zealand, Udby in S Zealand, and St.Vittingshøj, Freilevskov (with two monuments) and Mandemarke in Lolland-Falster. This inclusion of ¹⁴C-dated skeletal material from several passage graves in Scania and the Danish islands of Zealand and Lolland-Falster has the potential to unveil long-term uses of these monuments from their erection in MNA to continued interments in MNB, LN and even in the Bronze Age (work in progress). Substantial reuse of these stone graves is a well-known phenomenon, and individuals belonging to the 3rd millennium were therefore expected both in Zealand and Lolland-Falster as well as in Scania. The difference in sampling strategies between southernmost Scania and eastern Denmark, however, is due to the lack of MNB flat graves of Corded Ware type in eastern Denmark. Here, the megalithic FBC tradition simply continued in the MNB without major shift towards the flat grave inhumations in evidence in Jutland and in Scania (e.g. Iversen 2016; Winther Johannsen et al. 2024). The reason, however, for this striking deviation of Zealand, Fyn and Lolland-Falster from the nearby areas in Jutland and Scania is still unknown. Population decline is a possibility (Allentoft et al. 2024). The location of the CWC sites studied here is shown in Fig. 1. The Nordic CWC however comprises similar sites in Denmark, N Germany, Bornholm, S Norway, S Sweden, S Finland and the Baltic countries. We here define BAC burials as graves based on traditional regional CWC features and MNB burials as inhumations in megalithic graves since the cultural affinity of these individuals remains unclear.

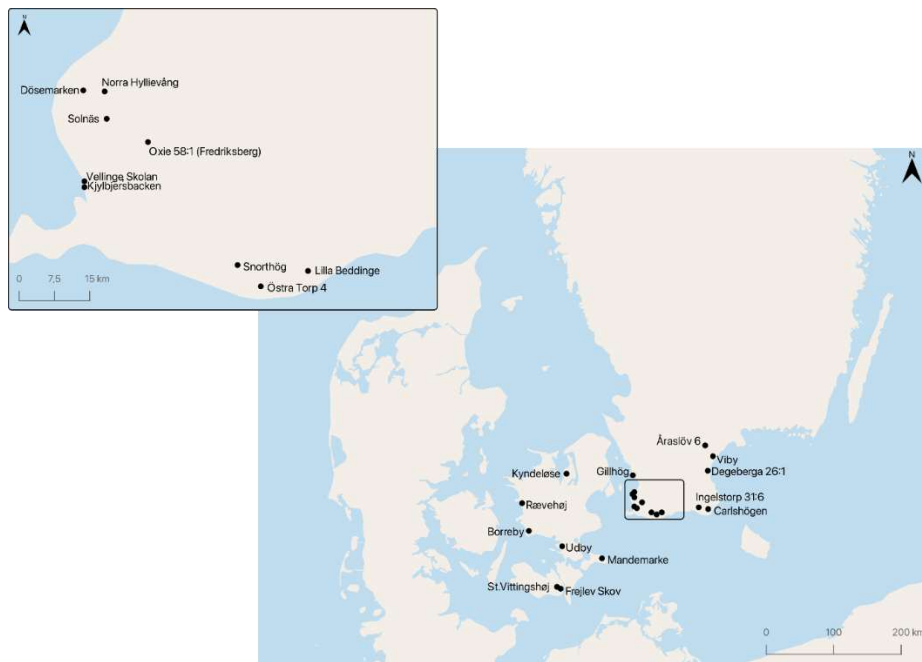


Fig. 1. Distribution of the studied sites in Scania and eastern Denmark. The southwest of Scania includes several sites in close proximity to one another therefore also provided in close-up detail. Figure: Cecilie Wilsborg.

Out of the total 45 individuals from Scania, 37 individuals were dated to 2600-2000 BCE. More precisely, the MNB/BAC sample comprised 27 individuals while the LN I sample comprised 10 individuals. An additional six individuals (with an equal number of teeth, i.e. one per individual), were analyzed for strontium data while depending on typological dating. After radiocarbon analysis, they were estimated to be of LN II-EBA I date (2000-1600 BCE) (n=5) or possibly of MNA date (3300-2900 BCE) (n=1). Two individuals could not be dated. The MNA individual derives from the original 'Farmer' population, namely the FBC who were the builders of the numerous megalithic passage graves in Southern Scandinavia.

The samples from eastern Denmark then spanned MNA to LN II/EBA: 12 individuals were dated to the 3rd millennium, while one was of MNA date and 11 were of LN II-EBA date. One radiocarbon date from the Borreby passage grave (Borreby 3) failed due to poor collagen preservation. However, since 10 other radiocarbon dates from this passage grave span between the LN I- EBA, it is plausible that this latter individual is of similar date. No earlier or later dates have been retrieved from the Borreby passage grave. A total of 18 individuals from Scania and Zealand pre-dating or post-dating the 3rd Millennium are included in the analysis for comparison with the MNB/LN I core data.

We primarily sampled teeth that form later rather than earlier, such as premolars and second and third molars (Hilson 1996: 124-125). However, for conservational and ethical reasons, we had to approach the samples in a pragmatic fashion and, on occasion, sampled canines, which are completed a little bit earlier in childhood (Gustafson & Koch 1974). Canines were sampled when extraction of premolars and molars was considered impossible without damaging surrounding bone or the extracted tooth itself.

Radiocarbon dating was conducted for all individuals included in this study or retrieved from earlier publications. The sources of radiocarbon data as well as information about all sampled teeth are provided in Supplement 1. Four individuals (Lilla Bedinge grave 47 cranium II, Lilla Bedinge grave 52 eastern individual, and both individuals from Degeberga 26:1) did not yield enough collagen for radiocarbon dating. A result was retrieved from an earlier publication showing a date in Early

BAC)(Supplement 1). The eastern individual from Lilla Bedinge grave 52 can, however, be dated to approximately 2492-2201 BCE with some confidence due to a successful previous radiocarbon date of the western individual inhumed in the same double burial (Allentoft et al. 2015: Rise 121). One of the individuals in the double grave from Degeberga was dated to c. 2659-2466 BCE using the newest calibration curve, corresponding to the Early BAC in typological terms (cf. Malmer 1962; 2002; Furholt 2003). Cranium II from grave 47 is more difficult to date since grave 47 includes bones from at least eight individuals (During 1988: 118-138) with significantly differing dates, spanning from MNB to EBA I (Allentoft et al. 2015; this study). Cranium IV in this assemblage has been dated to 2621–2306 BCE (Fornander 2013) corresponding to MNB. The primary burial was, however, dated to the transition LN II-EBA I (1877-1624 BCE) (this study: LuS 18065) and thus post-dates at least one of the crania over-layering the primary burial. It is possible that the five crania, together with other scattered bones in the covering cairn, were remnants from disturbed MNB graves (which may have been dug-through during the burial of the LN II-EBA individuals), which were then carefully redeposited.

Methods

Osteology

Adult sex was primarily estimated through dimorphic traits of the pelvis (Phenice 1969; Milner 1992) and secondarily by cranium morphology (Acsádi & Nemeskéri 1970). Sex estimation based on the cranium was predominant for the remains deriving from passage graves where the remains are commingled, and crania cannot be matched with pelvises. Sex was also determined through archaeogenetic detection of sex chromosomes in 22 individuals from Scania: 17 individuals from flat graves (Tornberg & Vandkilde 2025) and five individuals from passage graves (this study).

Adult age of flat grave inhumations was assessed through Transition Analysis³ (TA3) (Milner et al. 2021; Boldsen et al. 2022), a method based on advanced statistical and machine learning modelling of age traits throughout the skeleton. Adult age from commingled passage grave remains was estimated using dental attrition (Brothwell 1981) and all subadult ages were estimated through dental development (Ubelaker 1978; AlQahtani et al. 2010).

Radiocarbon dating

Radiocarbon dates within this project were carried out at the radiocarbon laboratory at the Geological department at Lund University, Sweden. The laboratory also carried out collagen extractions. The bone and tooth samples were first mechanically cleaned and pretreated with NaOH to remove humic and other organic impurities. Collagen was extracted using a modified Longin method (Longin 1971; Brock et al. 2010) and quality controlled through the C:N ratio (Brock et al. 2012). Only samples within the recommended C:N range of 2.9-3.5 were considered reliable and not biased by diagenetic circumstances. Ultra filtration was added for samples of poor quality to ensure that the samples were not contaminated. All calibrated dates are given in 2 sigma BCE and uncalibrated dates are available in Supplement 1 when available.

⁸⁷Sr/⁸⁶Sr analysis

Human strontium analysis was conducted by LA-MC-ICPMS at the Swedish National Research facility, Vegacenter, at the Swedish Museum of Natural History, Stockholm. Analysis employed an ESI NWR193 excimer laser ablation system mounted with a two-volume cell coupled to a Nu Plasma 3 MC-ICPMS. The analyses were conducted in four different sessions (April 2022, September 2022, March 2023, September 2023). The primary reference material was a fin spine from an oceanic velvet belly lantern shark (*Etmopterus spinax*). Secondary reference materials included teeth from a hare (*Lepus timidus*),

rodent (*Otomys sp.*), and sperm whale (*Physeter macrocephalus*), which covered a range of Sr/Ca ratios and were treated as unknowns during data reduction. Where space permitted, 12-13 equally spaced lines, oriented perpendicular to growth axis, were ablated from the tip of the tooth to the dentine-enamel junction (DEJ), thus covering the complete time of tooth mineralization. In single cases, less or more lines were ablated depending on the degree of attrition of the tooth (i.e. tooth height). Instrument settings, full data, and information about the standards are available in Supplement 2.

Strontium enters the human body through the food chain and incorporates in the enamel during mineralization via metabolically neutral substitution for Ca^{2+} . Hence, the laser ablation data provides information about the geological conditions of the individual, or the geological origin of the food and water, at different periods corresponding to the time that specific site of the enamel mineralized. The exact timing of mineralization of different sites of the tooth as well as the amount of time acquired for the strontium incorporation within each ablation line are still poorly understood. Studies of sheep teeth, however, show that spot-specific enamel mineralization occurs within only days to weeks but varies between different sites of the tooth; cusp enamel mineralizes faster than cervical enamel (Green et al. 2017). Earlier studies suggest that the incorporation of strontium is rather fast in humans as well and that each ablation line signals the strontium averages of only a few weeks (Boethius et al. 2022a). Considering these limitations, it is problematic to assess the exact time spent in specific areas as well as the exact age to which each value relates. In this paper we therefore consider mobility and variations in strontium ratios more broadly within the age interval that corresponds to the formation of the tooth crown as suggested by Gustafsson and Koch (1974).

Baseline data of bioavailable strontium has been obtained through earlier publications and plotted to provide an isoscape (Fig. 2). The geological conditions are different within Scania, where the northeastern part expresses rather patchy geological conditions with a variety of Sr isotope signals within a limited area, whereas the southwestern part is extremely homogeneous. Ladegaard-Pedersen et al. (2021) established four different areas (1-4) based on multi-proxy data. This study provides important data, though those data remain nevertheless difficult to employ, as the strontium ranges within area 2 (NE) also encompass the ranges of area 3 and 4 (NW-SE & SW) which share the same strontium isotope range. This makes mobility analyses in relation to local vs. non-local problematic since some of the areas could not be separated from others. However, despite these circumstances, it still enables analyses of strontium data variation which better pinpoints movements over short distances. The data from Ladegaard-Pedersen et al. (2021) is the primary baseline source for Scania in our study but has been completed with additional baseline data from other studies (Boethius et al. 2022b: Supplementary file1; Macheridis et al. 2024a: Table 1; Macheridis et al. 2024b: Table S2). Danish bioavailable strontium data has been obtained through the publication by Frei et al. (2022: Table S1).

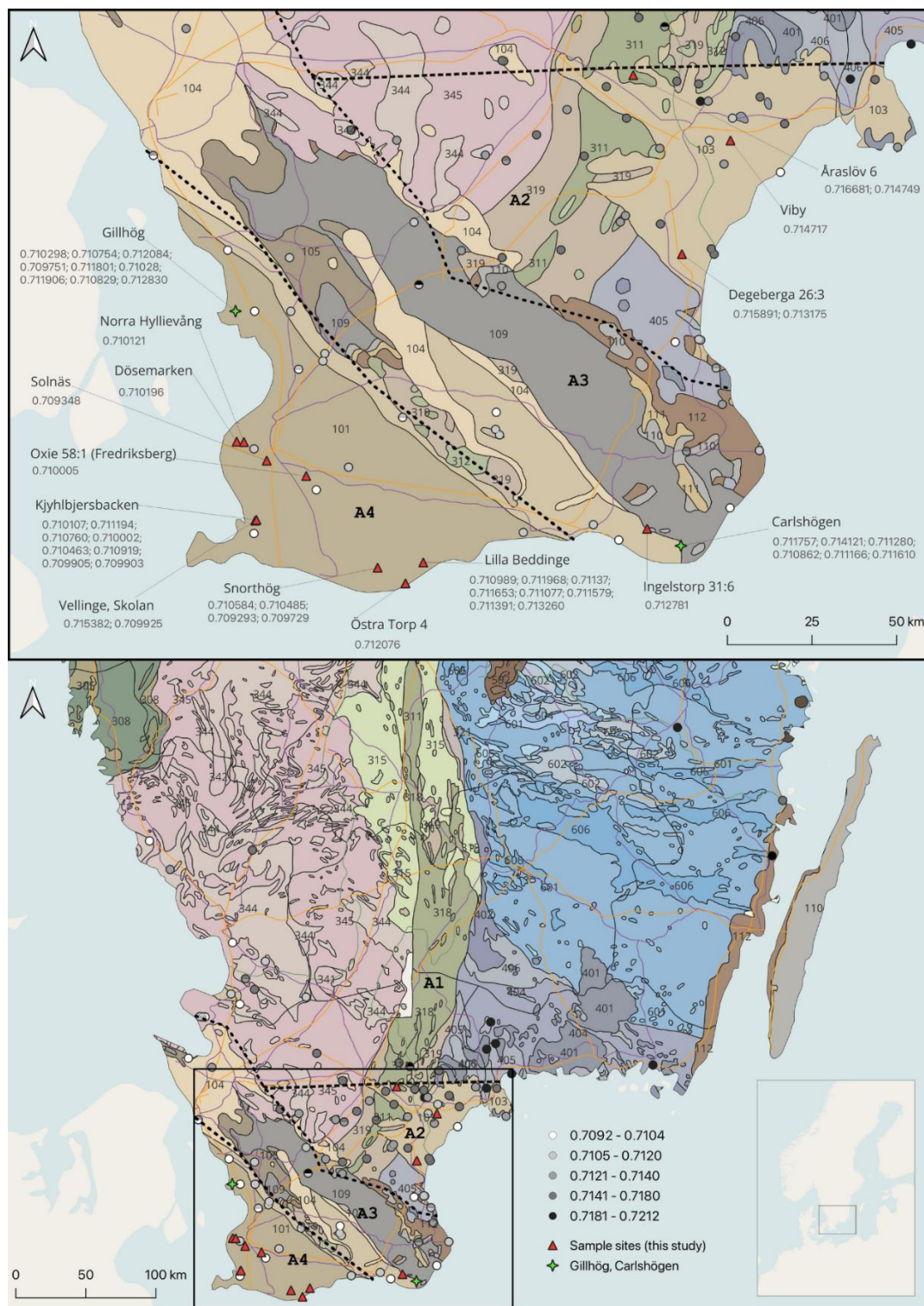


Fig. 2. Baseline values and sample sites in Scania. The map is subdivided into area 1-4 as suggested by Ladegaard-Pedersen et al. (2021). Green stars indicate passage graves. Baseline values are based on previous publications (Ladegaard-Pedersen et al. 2021; Boethius et al. 2022b; Macheridis et al. 2024a; 2024b).

Results

Contrary to bulk strontium data, spatially-resolved data contribute not only to improve understanding of individual mobility on a local or non-local scale, but also to variables such as chronology in addition to burial practice, violence, and sex/gender. It is even possible to target more complex scales of movement into or outside of the local area. We applied statistical tests of variance (f-test) between individuals and groups to get insights into possible variability in movement that was not only dependent on local/non-local gradients. Because of differences in bioavailable strontium ratios and burial circumstances, the sample is subdivided into a Scanian and a Danish segment in the following. Chronological information about all individuals is available in supplement 1.

Scania

Of the total number of 50 teeth/45 individuals from Scania, only two individuals showed strontium isotope averages corresponding to non-local signals if compared to the Areas 1-4 by Ladegaard-Pedersen et al. (2021): one female BAC individual from Vellinge Skolan (Srl mean: 0.71538) and a male LN II individual from Löderup 78 (Srl mean: 0.71628). The individual from Löderup 78, however, post-dates the timeframe in focus in this study and is, therefore, not investigated further here. Both individuals evidenced strontium values exceeding baseline values of Area 3-4 and have the closest match in Area 2. There is, however, visible variation in the dataset, within and between individuals. Two individuals (an MNB individual of unknown sex from Carlshögen and a BAC male individual from Lilla Bedinge) evinced variations in the ablation measurements that intimates that these individuals moved in and out of the local area even though the mean value indicated local origin (Fig. 3a, d). In the case of the non-local female from Vellinge Skolan (Fig. 3c), the last strontium value corresponds to local signal, which might indicate the time at which she settled in the area where she was later buried.

Fig. 3 A-D. Ablation strontium data from Scania (n=50) subdivided by local baseline areas 2-4 according to Ladegaard-Pedersen et al (2021). Area 1 is not represented by any samples. X-axis corresponds to the ablation lines; the first line corresponds to the highest position of the crown and last line to the Dentoenamel Junction DEJ. The data from area 4 is also subdivided between sexes due to sufficient sample size. The data supports substantial variation in strontium values for some of the individuals which indicates local movement of 30-50 km on regular basis or variation in food resources. Two individuals evidence movement in and out of the local baseline while the female from Vellinge seems to have moved into the local area in her teens. The more diverse values in area 2-3 plausibly correspond to the higher variance in Sr baseline values in these areas than in area 4 which is profoundly homogenous. Squares= MNA; Triangles= MNB; Circles=LN-EBA. Dashed indicates males, dash/dotted indicates unknown sex/gender, and solid lines indicates females.

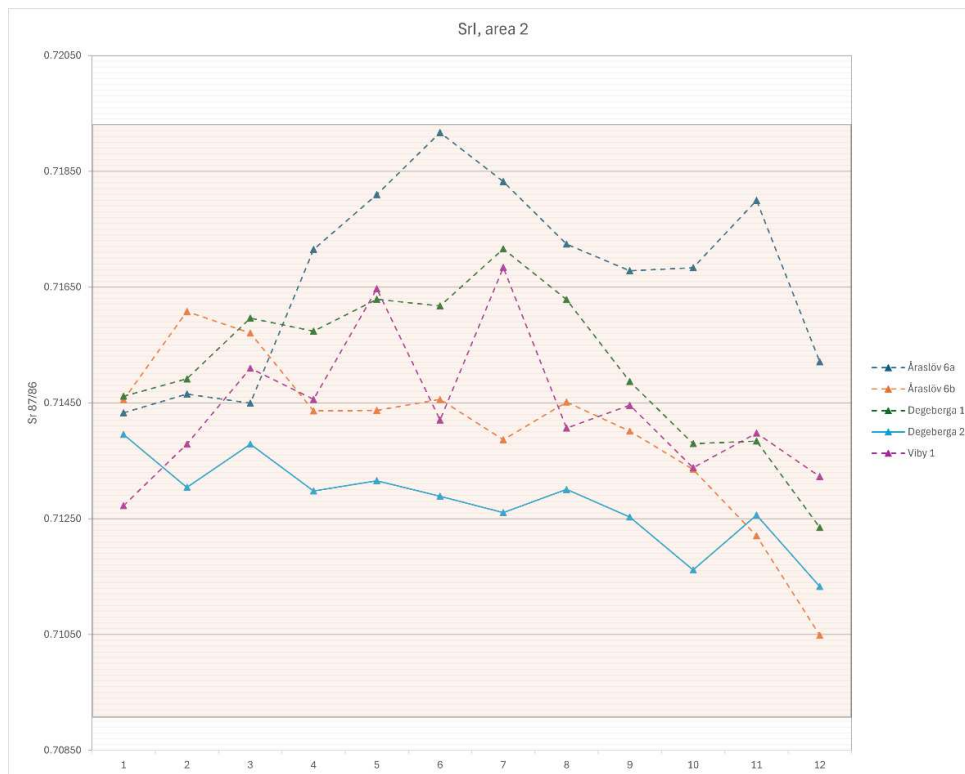
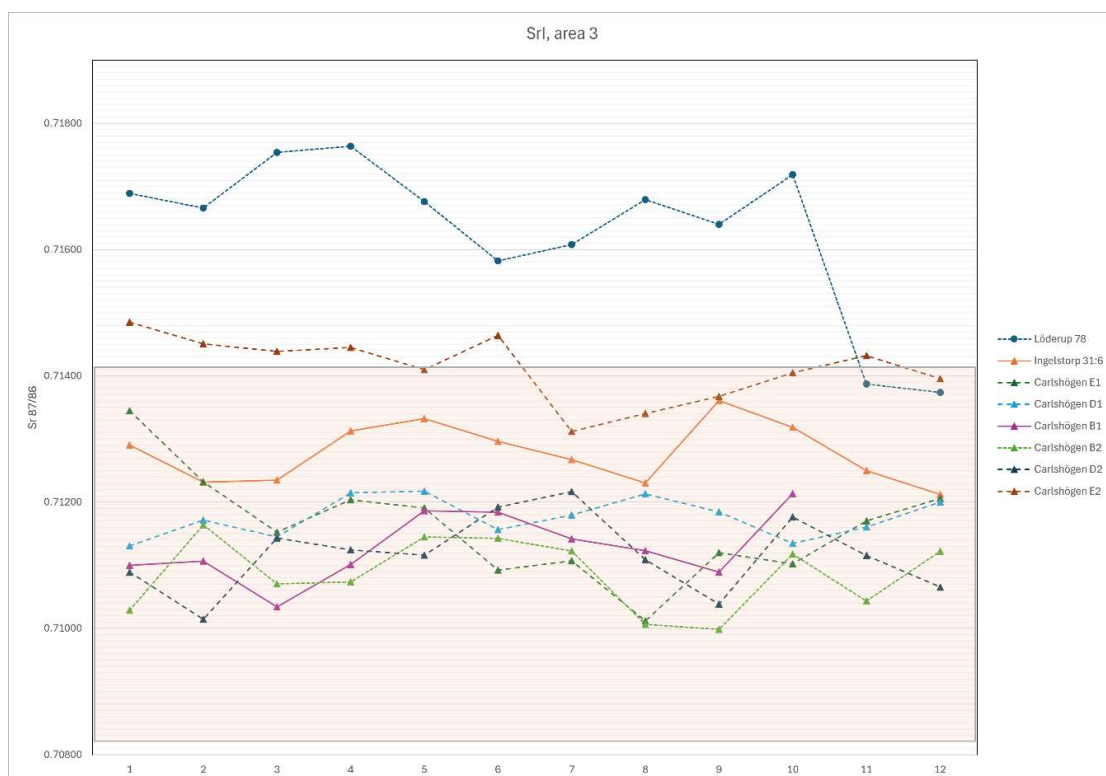
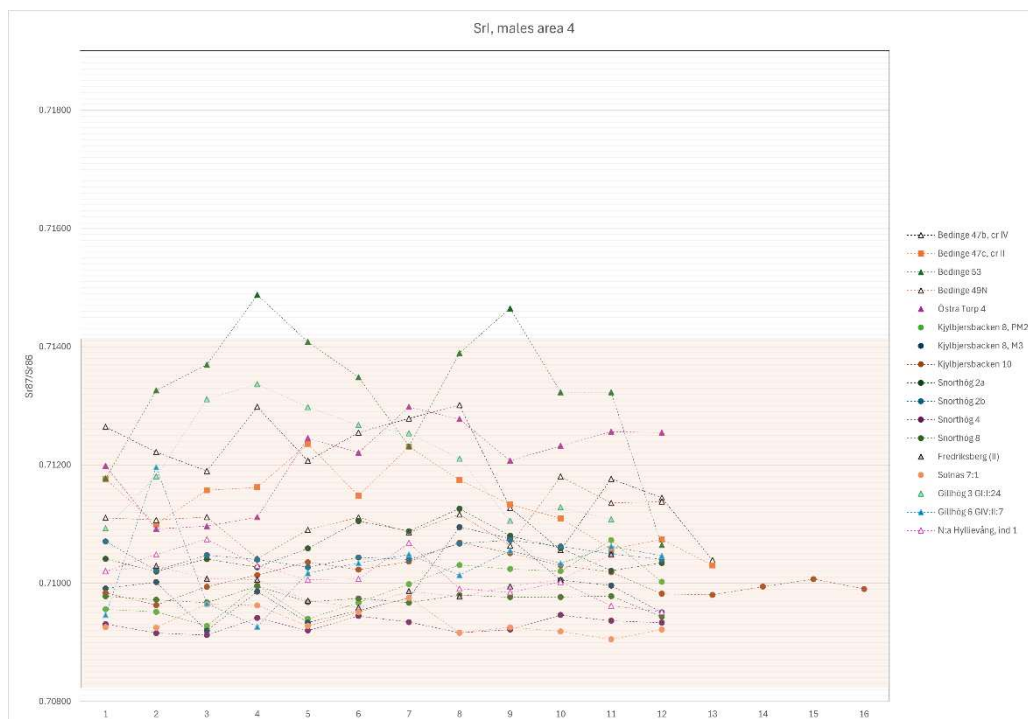
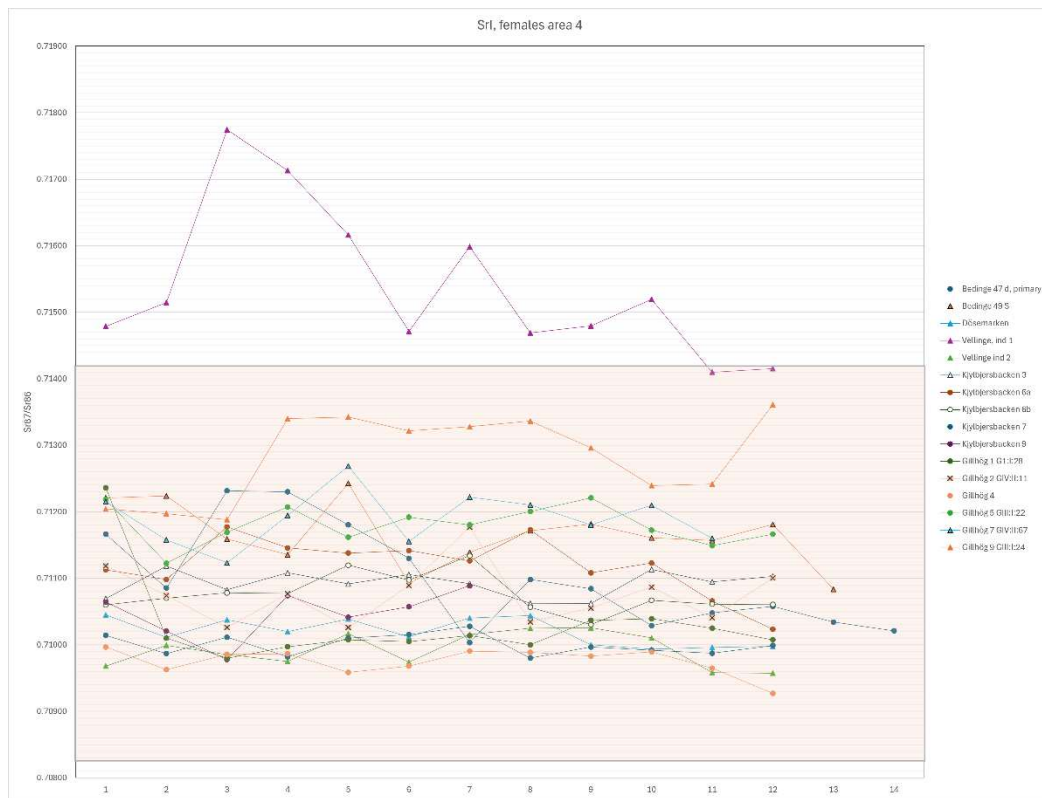


Fig. 3a. Strontium isotope values from area 2. All individuals fall within the wide local bioavailable baseline, however with substantial variance within and between individuals. The two different teeth sampled from the same individual from Årslöv 6 show significant difference in strontium values, indicative of changing environments between ages.



The strontium values from area 3 supports limited movements inside the local area for most individuals while the LN individual from Löderup have clear non-local values in the first measurements while falling within the local range in the last two lines. Individual E from Carlshögen shows local values in the canine (E1) while the third molar shows values indicative of moving in and out of the local area (E2).



To better gain insight into mobility over short distances within the different Scanian areas, we subdivided the areas based on the geographical locations of our samples; the areas were subdivided into West, South-West, South (Area 4), South-East (Area 3), and East and North-East (Area 2), in accordance with the divisions laid out by Ladegaard-Pedersen and colleagues (2021). To gain information about the strontium variability within each subarea, we collected all values from all individuals and plotted them to gain better understanding of variation and outliers in the data (Fig. 4). The boxplot evidence substantial variation in the data which primarily reflects the homo- or heterogeneity of the local bioavailable strontium signals but might partly also reflect a difference in mobility/utilization of variable sources between different subareas. There is more variation in strontium data in the subarea SE which falls within Ladegaard-Pedersen et al. (2021) area 3 related to the western groups in area 4 although area 3-4 are given identical baseline ranges.

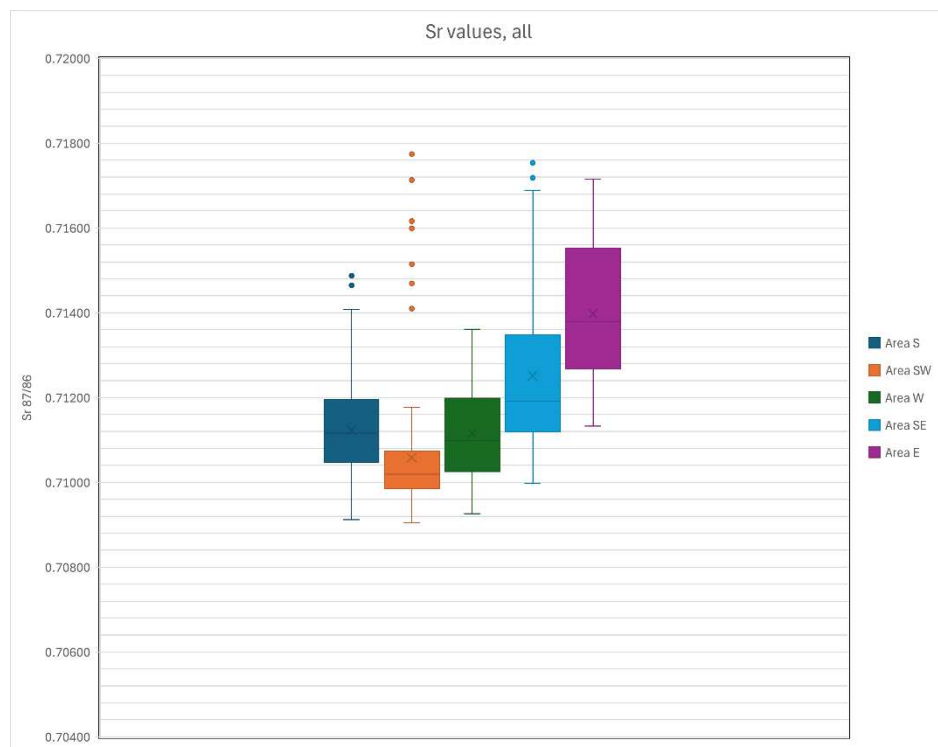


Fig. 4. Boxplot of all strontium values divided into the different subareas. The plot clearly shows that there is high correspondence of data in SW while the difference in data is significantly greater in NE. This pattern corresponds to the homo- and heterogeneity of the baseline data in each area. Outliers are available in area S, SW, and SE and correspond to values from individuals determined as non-locals when comparing to Ladegaard-Pedersen et al. (2021).

To gain deeper understanding of individual and group mobility related to life histories, we assembled a variety of data and related them to the strontium values. We analyzed possible relationships between variance in strontium values related to burial practice in the MNB sample (flat graves with single and multiple inhumations versus megaliths), as well as biological sex, and relative chronology (MNB/BAC vs LN I-LN II) in the total 3rd Millennium BCE sample. The individuals that had ¹⁴C-dates spanning from MNB to LN I were considered MNB in our calculations when most of the confidence interval belonged to the MNB.

To exclude bias in the modelling depending on age of tooth formation, we tested if there were differences in variance between early and late forming teeth. There was no statistically significant difference between teeth and could thus be excluded as explanatory factor ($p = 0.404556$). Since ten teeth from Scanian megalithic passage graves ranged within the MNB, we also tested if there were significant differences in the variation in strontium values dependent on burial practice. We only

included individuals from Area 3-4 because of the narrower and more concise baseline levels as well as the abundance of analysed individuals. Despite questioning by Olausson (2014; 2015), Horizon A CWC and particularly BAC grave goods are quite frequently retrieved from passage graves and dolmens even if they are surely outnumbered by the BAC flat graves in small family cemeteries (Malmer 1962; 2002). Considering the relative frequency of skeletal material in passage graves that is ¹⁴C-dated to the BAC period, it is pertinent to assume that finds of common BAC-type grave goods reflect actual BAC burials. There is a striking material difference between burials in megalithic chambers and in flat grave cemeteries that might be reflective of social hierarchies or other sociocultural phenomena. Although there seems to be a higher variance in strontium values in the traditional BAC burials, the difference does not reach statistical significance ($p=0.067657$).

Since there is limited data on the sex distribution of Area 3, and Area 2 only encompassed male individuals, our test of differences in the variation between the sexes was based on Area 4 only. We found no statistically significant difference in the variance dependent on sex/gender ($p= 0.643589$). There seems to be no difference in the level of mobility between the sexes/genders if the complete MNB-LNI sample is considered ($p= 0.1002948$). The only significant difference in the variance of strontium was found between the chronological divide of BAC/MNB and LNI-II in Area 4, the wealthy SW Scania ($p=0.045772$) (Fig. 5). Here, we included both sexes and both burial types since none of these variables showed contributions to the variance in strontium. Furthermore, we explored the possibility of differences in mobility related to evidence of violence in the complete 3rd millennium Scanian dataset subdivided between areas. Individuals that could not be assessed due to taphonomic loss were excluded. As it turned out, the number of individuals with evidence of violence related trauma within each area was too small to measure significant differences, and there were no noticeable trends. In area 2, the individual suffering from violence (perimortem) exhibited a lower variance in mobility than the non-affected individuals' average value ($n=3$), while the individual suffering from violence in area 3 (antemortem) exhibited substantially higher standard deviations in the data related to the three non-affected individuals. Area 4 included four individuals with signs of violence (all antemortem) whereas 27 individuals were not affected. The difference is small with only marginal higher values in the affected group (table 2). Noteworthy, however, is that both the male individual in Lilla Bedinge grave 53 and the individual E2 in Carlshögen (possible male) both suffered from antemortem skull trauma as well as having variance in Sr data suggesting moving in and out of the local area. The individual from Lilla Bedinge was also buried with an antler pick-axe, which is known to have been used in war. This is evidenced by a find of a similar pick-axe still embedded in the skull of a contemporaneous individual in Tygelsjö, Scania (Fibiger et al. 2023).

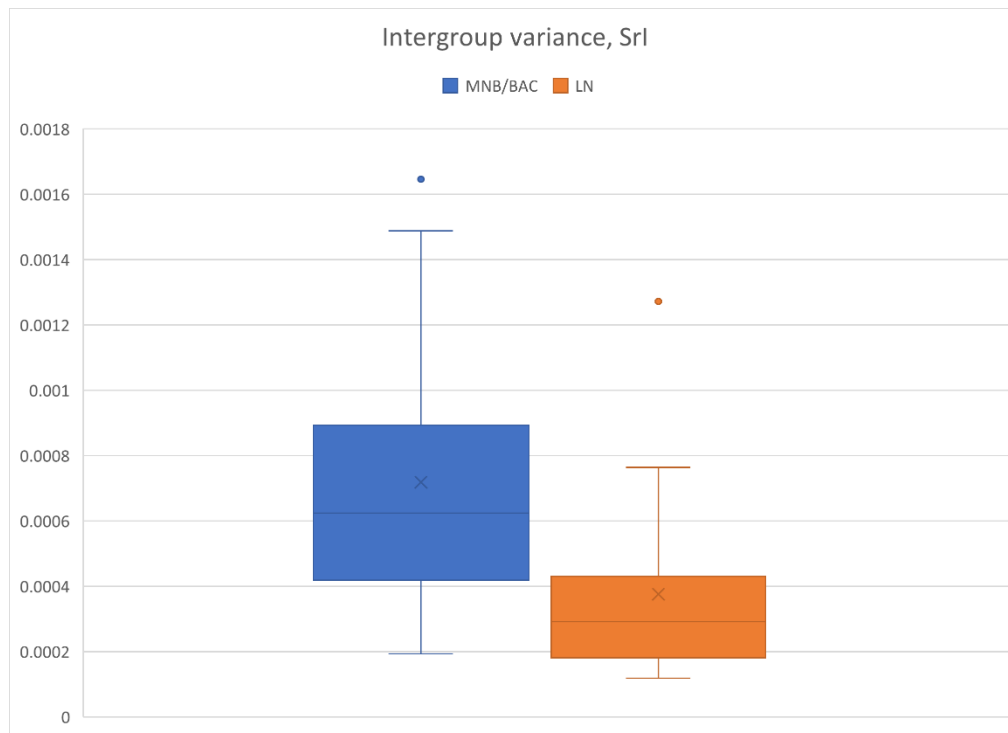


Fig. 5. Inter group variance of laser ablation strontium values of males and females in area 4. The MNB/BAC population exhibit significantly higher variance than the LN population in the area, which might correspond to differences in mobility related to subsistence and/or cultural practices.

Table 2. Variance in mobility, reflected in average standard deviations, between individuals suffering from violence related trauma and individuals without skeletal signs of violence divided between the three Scanian areas under study. There seems to be no difference in mobility patterns between the two groups, although, the number of individuals in each group is limited due to the subdivision.

	VIOLENCE		#	NON-VIOLENCE		#
AREA 2	0.001231	1		0.0015	3	
AREA 3	0.000846	1		0.000485	1	
AREA 4	0.000598	4		0.000458	27	

We also compared the strontium values for everyone with the closest matching baseline data in order to trace possible mobility patterns (Fig. 6). Differing individual patterns are indicated through dashed arrows. Generally, mobility seems to be concentrated on shorter distances of up to 25-30 kilometers or less and seems to have been continuous. It is plausible that this kind of movement is related to seasonal practices associated with pastoralism, though other seasonal practices of sociocultural meaning would create similar patterns. It is obvious that the more varied bioavailable strontium levels in the NE provide better resolution for the sequential strontium data, and it is highly likely that mobility is more pronounced in the S and SW than is detectable in the strontium data due to the very homogenic strontium values over large distances which characterize this area. In some instances, the individuals from the S, SW, and W have lower strontium values which may plausibly have been affected by marine dietary contributions (Andersson et al. 1992). This assumption is partly confirmed by published stable isotopes from the Snorthög site (Tornberg 2018), where the individual in grave 2 has elevated ^{15}N values (11.3 ‰) and less negative ^{13}C values (-19.9 ‰), suggesting some marine contribution. The stable isotope analyses were, however, conducted on bone instead of teeth, and do

415 not, therefore, correspond to the same time period in the human lifespan. The stable isotopes do not
416 as readily confirm a marine contribution in other individuals in Snorthög (grave 4, 8); grave 8 has
417 strontium values indicative of marine input while the stable isotopes conducted on bone collagen
418 correspond to a completely terrestrial diet.

419 Although most individuals in the S and SW provide very similar strontium values with low degrees of
420 variation, the two male individuals buried in Östra Torp no 4 and in grave 53 in Lilla Bedinge show some
421 strontium values that have the closest proximity to the NE and suggest that they spent some of their
422 childhood at least some 50-100 km from their site of burial. The older adult female from Vellinge
423 provides non-local values throughout the dataset, except for the last value, which also finds the closest
424 proximity to the NE. One possible female individual dating to the MNB/LNI transition from Gillhög
425 passage grave also evidence non-local signals in the later values (corresponding to c. age 5-6) which
426 means that she probably spent substantial time elsewhere during her childhood. A possible male
427 individual from the Carlshögen passage grave (E1/E2) had two teeth sampled (canine and third molar)
428 which show somewhat differing strontium values. The early-forming canine shows strontium values
429 which correspond better to areas to the N or NW while the strontium values in the late forming third
430 molar are lower and may represent local values. It is highly likely that this individual spent his early
431 childhood in areas north of the burial location and moved into the area in late childhood/early
432 adolescence. The opposite pattern is visible in the individual from Åraslöv where a second and a third
433 molar were sampled. The second molar showed local values while the third molar had decreasing
434 strontium values with an end value which best corresponds to SE Scania. The two individuals buried
435 together in Degeberga both had local strontium values, though individual 2 evidenced somewhat lower
436 values corresponding to areas further N or S. Individual 1 have a probable male sex according to sex
437 chromosome analysis while the sex of individual 1 could not be determined, either through osteology
438 or aDNA. Following the general burial custom of the CWC/BAC, the individual should be of female sex.
439 The male sex for the second individual follows this burial pattern.

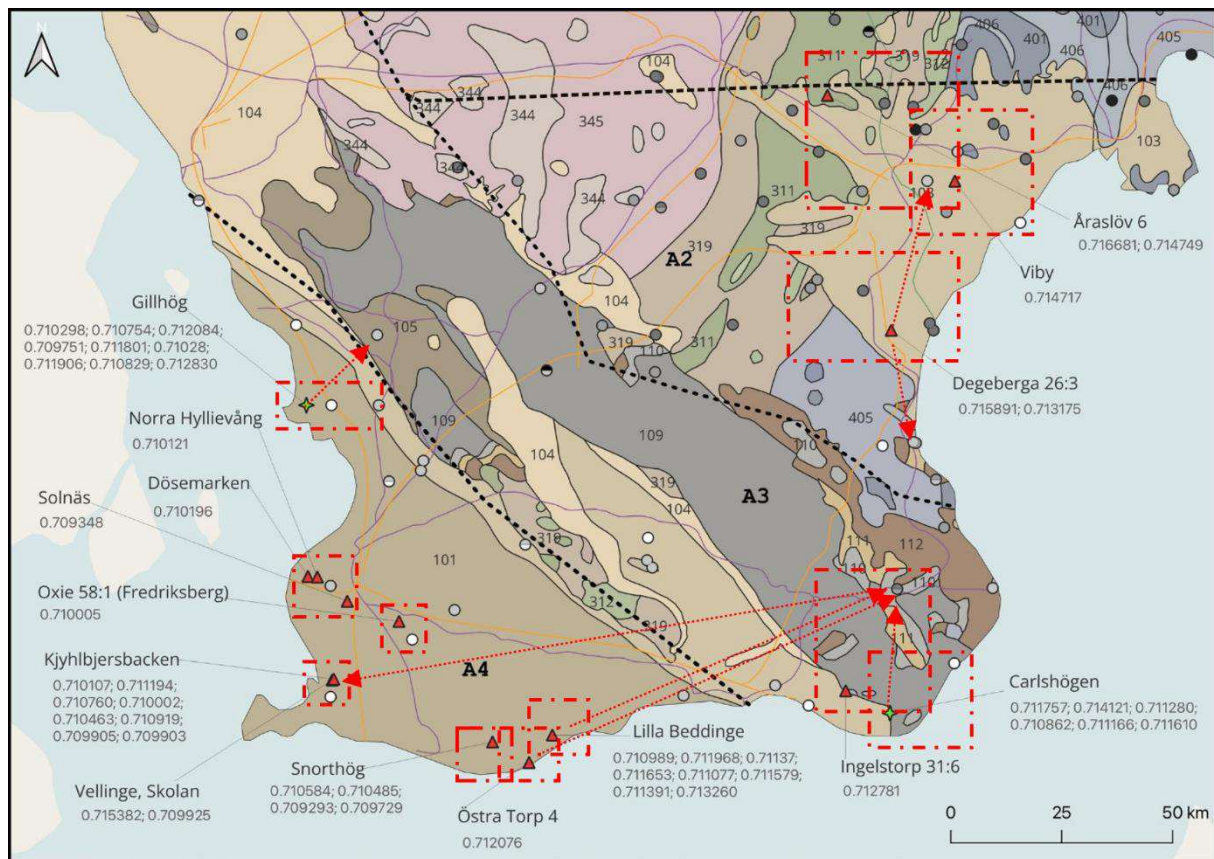


Fig. 6. Potential mobility ranges for the 3rd Millennium individuals in Scania based on previously published baseline data. Individuals with values deviating to the range are marked with a dashed arrow to the closets area with a measurement of corresponding baseline value. Direction of the arrows are aligned with estimated direction of movement.

Denmark

Due to the lack of single grave burials on the island of eastern Denmark, we instead targeted individuals buried in megalithic passage graves. Considering that the graves encompassed several commingled inhumations, we could not discriminate 3rd millennium individuals from earlier and later ones without radiocarbon dating. We therefore performed radiocarbon dating on a total of 99 unique individuals retrieved from 11 different passage graves to secure the temporal origin of the inhumations. Two of the samples were of insufficient quality (Borreby 18 and Rævehøj 24), leaving us with 97 dated individuals (Supplement 3). The data supports a significant reuse of the passage graves in the LN. This trend notably began in the Late BAC phase while peaking prior to 2000 BCE when the first influx of metal commenced (Fig. 7). However, not all individuals were subjected to strontium isotope analysis. We managed to retrieve strontium data from 25 individuals. The radiocarbon dating demonstrated that only one individual sampled for strontium could be associated with the original TRB population with a 14C date corresponding to MNA (Frejlev Skov cranium VII) and that only two individuals, both from the passage grave of Kyndeløse (crania XXII and XXVI), could be securely dated to MNB, while one individual from Rævehøj (cranium XVI) had a date spanning from MNB into LN I. The remaining 20 individuals in our sample all fell within a Late Neolithic range: nine corresponding to LN I or transition LN I-LN II, and 11 to the LN II or transition LN II-EBA.

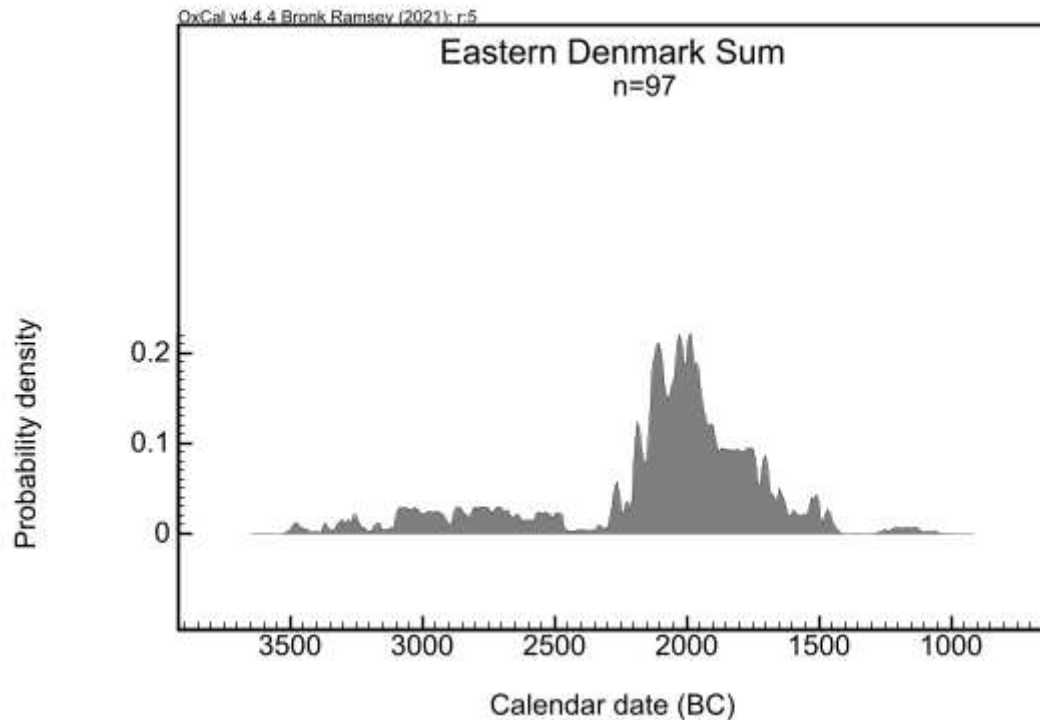


Fig. 7. Sum plot of all radiocarbon-dated individuals from selected megalithic monuments in eastern Denmark (n=97). The result shows increasing use already in the Late SGC (CWC) followed by a marked peak at the start of LN II c. 2000 BCE, when the first metal rush began, continuing into the earliest Nordic Bronze Age. From around 1500 BCE megalithic monuments were rarely used as burial space. Figures created using Oxcal 4.4 online.

The bioavailable strontium in eastern Denmark is even more homogenous than in Scania, which significantly limits the analysis. However, eastern Denmark is generally considered to have baseline values spanning between 0.7089 and 0.7108, while western Denmark exhibits even lower strontium values. When considering average strontium values of the individuals, none were established as non-local. However, when evaluating the different ablation lines, we identified considerable movement in some of the individuals both within, and possibly outside, the local baseline (Fig. 8). The three individuals who expressed the highest variance in strontium values were the samples from Kyndeløse, which might correspond to more varied baseline values in closer proximity to this site than others. The two possible male individuals from Kyndeløse with an MNB date also showed the highest variance (SD= 0.000557864 for cranium XXII and 0.001235334 for cranium XXVI).

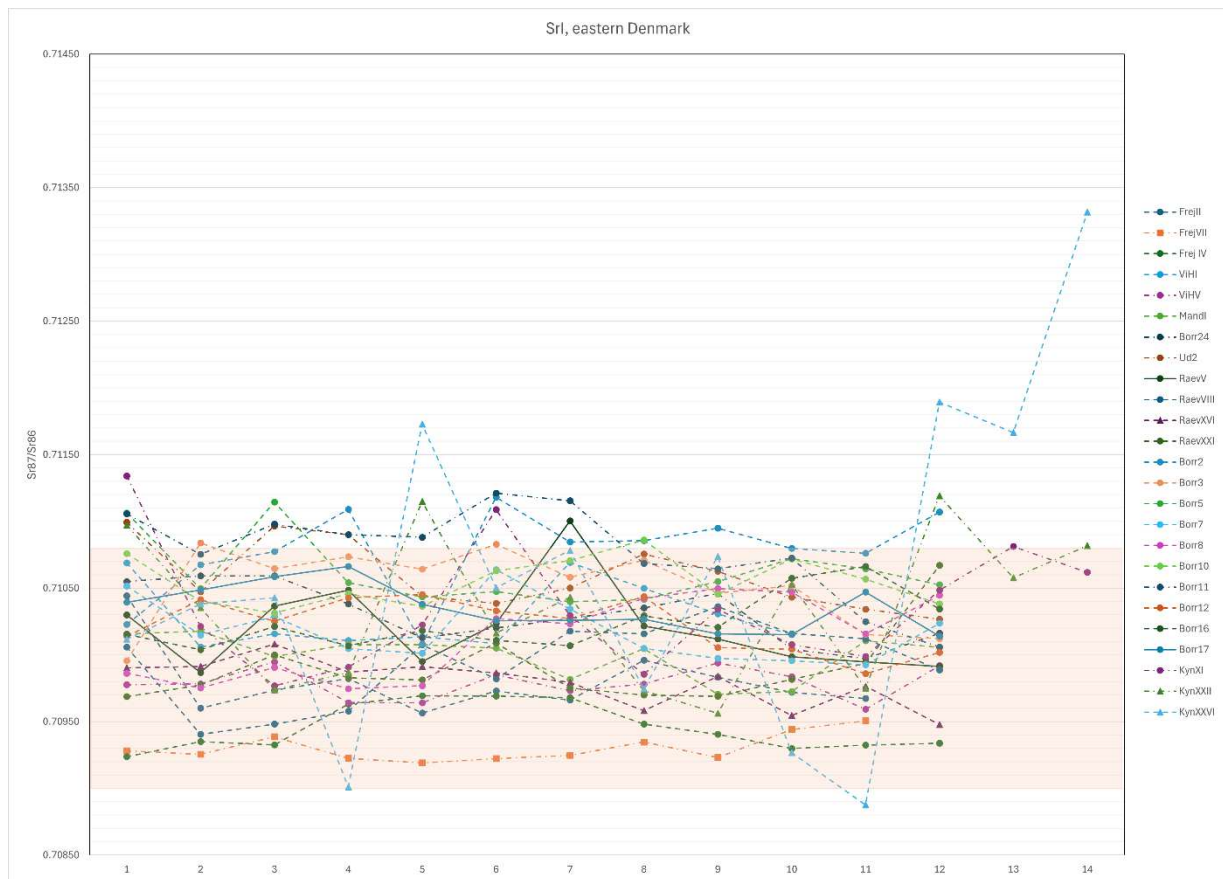


Fig. 8. Laser ablation values of the Zealandic sample (n=25). Most individuals display rather homogenous values, but the individual Kyndeløse XXVI (MNB date) evidence substantial variation within the data set. The lowest values might indicate marine contribution to the diet. The local baseline value is here set to the average for eastern Denmark (0.7089-7108) (Frei et al. 2022, Table S1). Squares= MNA; Triangles= MNB; Circles=LN-EBA. Dashed indicates males, dash/dotted indicates unknown sex/gender, and solid lines indicates females.

While most Sr values identified in our sample have corresponding values in baseline samples from Zealand and Jutland (Frei & Price, 2012) some distance away to southwest, the individual Kyndeløse XXVI evidenced one period of occupation with a relatively high strontium value (0.71332) for eastern Denmark. Frei et al (2022) provide predicted baseline (soil leaches and plants) of up to 0.714 to the west of Kyndeløse and even higher values to the southeast and northeast of the site (Fig. 9), which would be the closest proximities. This would correspond to a distance of approximately 50 km.

Though the sample size is limited, we could not detect any difference in mobility between the sexes. Only three individuals could be assessed as females and 15 as males or likely males in the total sample. Distinct male sex bias is significant both in the Danish megaliths and in traditional Nordic CWC graves and points to differences in burial practice between the sexes/genders, especially in the early phases (Tornberg & Vandkilde, 2025). The average standard deviation in females was 0.000280 and 0.000237 in males, which then correlate with the pattern seen in Scania with similar types of mobility among the sexes. There is no obvious difference in mobility patterns between individuals suffering from possible violence related trauma (n=4, SD average 0.000291009) and unaffected individuals (n=19, SD average 0.00030353), either.



Fig. 9. Baseline map and sites selected for strontium isotope analysis in eastern Denmark. Individual XXVI in Kyndeløse exhibit some relatively high strontium values for eastern Denmark but has closest proximity in the southwest of the site only tens of kilometers away. Figure by Cecilie Wilsborg.

Discussion

Here we put forward the most comprehensive study of prehistoric mobility in Southern Scandinavia to date. We explored mobility through 903 spot measurements of strontium isotopes from 70 Neolithic

individuals from Scania, southernmost Sweden, and in eastern Denmark. Both eastern Denmark and Scania exhibit baseline values that overlap and are rather homogeneous over large areas. Generally speaking, this biases evidence of mobility negatively, especially when conducting traditional bulk strontium analysis. Here we show that, although the vast majority of the individuals provides local strontium values on average, there is indeed substantial mobility and, thus, utilization of different landscapes on a local scale. The latter is especially visible in the larger Scanian sample.

There is nothing in the dataset that could be associated with the demic diffusion that completely changed the genetic and sociocultural landscape of Southern Scandinavia in the early 3rd millennium BCE which would in turn indicate long-distance travels, or even permanent relocation from geographical regions far away. This 'black box' situation may not be surprising, considering that Early CWC burials with preserved skeletal remains – suited for Sr and genomic analysis – are very rare in Scandinavia overall. Most CWC/BAC finds in Scania containing osseous remains are generally from the Late BAC and LN I phases (2350-2000 BCE). Although the individuals from the Carlshögen passage grave were ¹⁴C-dated to early MNB (thus, contemporaneous with the classical phase of early CWC expansion commencing c. 2900 BCE), there is nothing in the strontium values that suggests long-distance movement either.

Based on the strontium values now available, we instead argue for a consolidated community characterised by a local-range routinised mode of mobility in Scania notably in the later part of the CWC/BAC (c. 2350-2250 BCE) and continuing into LN I (2250-2000 BCE). In terms of material culture and mainly grave goods, the transition between these two phases was gradual throughout Scandinavia. The range of movement would primarily be shorter than 50 km in both Scania and eastern Denmark, but there are exceptions visible in the Sr values exceeding the local baseline values. Although this might seem undramatic, it correlates rather well with the well-explored mobility data from Falbygden which is based on bulk strontium isotope analyses (Blank 2021:81). Although a large part of the buried population corresponds to non-local values, most of these values are found just outside the geologically distinct area of Falbygden (50x30 km) and would, thus, primarily be associated with mobility over rather short distances of only tens of kilometers. This pattern changed in the LN II/EBA (c. 2000-1600 BCE) when mobility changed towards longer distances due to the demand for bronze. Our sample from this late period is too small to evince patterns which either support or deviate from this.

The significantly higher degree of short-distance mobility in the BAC/MNB relative to LN, visible as a statistically significant higher variance in SrI data, might be affected by differences in subsistence practices and, perhaps, a generally more mobile and volatile society. The infrequent evidence of permanent settlements until the very end of the Nordic CWC has often led to the conclusion that these populations were mobile pastoralists (e.g. Malmer, 1962; 2002; Ebbesen, 2006:147). It is possible that the range of movement corresponded to set territories within which pastoral lifeways could be pursued without trespassing neighboring groups' territories (cf. Lazzerini et al. 2021, for ranges associated with sheep pastoralism). Such territorially-constrained pastoralism may have been a necessary supplement to household-based crop farming. A semi-sedentary economy, or agropastoralism, would work very well with the considerable population growth which occurred in the BAC-LN I period (Tornberg & Vandkilde 2025). Depending on population density and resource abundance and variability, it is likely that the size of these territories and the need to protect those territories differed (Moritz et al. 2020). The longer ranges in the Scanian west seem to be oriented eastwards rather than to the north (possibly a data artefact caused by deviating baseline values). Nonetheless, a mobility directed SW-SE is of interest, since both these areas were highly significant during the LN-EBA and may well have originated in MNB networks. The northeastern area seems to,

likewise, demonstrate some mobility directed towards the eastern and southeastern coastal areas. In terms of the few cases of elevated longer-range mobility, it is striking that the only two individuals of MNB date in the Danish sample both exhibit the highest variation in strontium values and that one of the individuals provides very high strontium values for eastern Denmark. This individual (an adolescent or young adult male), moreover suffered from a perimortem skull trauma (Tornberg et al. forthcoming).

The complete Srl dataset has a male sex bias which limits the analysis of sex-based differences in mobility. The distinct male sex bias as defined in biological terms reappears in its cultural form—social gender—in the burial practices where we sampled broadly. Males did in fact receive burial more often than females. The only areas where sex/gender differences could be explored in more detail were in area 4 in Scania and in eastern Denmark, both in areas which exhibited the most homogenic baseline values. Due to these circumstances, it is possible that there are actual sex/gender differences in mobility but that the values are so similar for a large area that such differences do not manifest in the data. In reference to what has often been assumed to be patrilocal and patrilineal societies in Neolithic Scandinavia (Seersholm et al. 2024), a lack of sex/gender differences in the mobility data might seem surprising. However, moving into new family groups might be expected in adolescence or young adulthood (Massy et al. 2017; Mitnik et al. 2018). Our female sample (area 4 and Zealand) is skewed towards female children and adolescents (n=10) rather than adults (n=7) which might also influence the data. These females would as such primarily be expected to be local and not yet to have relocated into a new family group. The old adult female from Vellinge (individual 1), however, evidence non-local strontium isotope values throughout the third molar sampled in this project but nevertheless expresses a local signal from the last ablation line. Considering that the mineralization of the third molar corresponds to adolescence, it is plausible that the shift in strontium values between the earlier and latest ages of tooth mineralization could correspond to mobility related to patrilocal exogamic marital practices. A small study of sequential strontium isotopes in LN II-EBA gallery graves in Falbygden, southwestern Sweden, however, suggests sex differences in mobility were already apparent in childhood with males being the more mobile (Blank et al. 2025). This pattern might relate to early inclusion of male children in pastoral transhumance while female children were incorporated in activities close to the settlement. However, larger datasets are necessary for definite conclusions. If this relationship would hold true, the similar patterns of CWC/MNB males and females might correspond to a more defined pastoral community where both sexes were involved in herding instead of a LN sedentary agriculture with a gender division in household responsibilities.

This assumption is somewhat strengthened by paleodemographic analysis which supports substantial intercommunity contact during the Nordic CWC in comparison to contemporaneous and subsequent populations (Tornberg & Vandkilde 2025). CWC subadult mortality data was compared to populations of the Swedish Pitted Ware Culture, the Late Neolithic-Early Bronze Age, and 18th century church records of the parish Gustav Adolf in southernmost Sweden using the Death Rate Ratio (DRR) (Paine & Boldsen 2002). According to Paine and Boldsen (2002), DRR is low-moderate in populations with low intercommunity contact, while it drastically increases when intercommunity contact is higher. In populations with high intercommunity contact (such as urban societies), the DRR drops to very low levels due to the recurring infections which elevate infant mortality. In the CWC, we do see DRR ratios which were substantially higher than the contemporaneous PWC, and moderately higher than the following LN-EBA. This pattern, thus, indicates that the CWC populations of Southern Scandinavia were involved in intensified intercommunity relations which correspond very well with the strontium isotope data presented here.

Nordic CWC classifies as a deviant among Neolithic groups in Southern Scandinavia due to several grounds: the cultural tradition of flat graves boasted distinct gender differences and, very often, a male warrior ethos, elevated mobility, demographic signals of high intercommunity contact and high levels of violence. By comparison, the LN I was less mobile, expressed somewhat lower levels of intercommunity contact (Tornberg & Vandkilde 2025), and substantially lower levels of violence (Tornberg 2022). A plausible scenario to explain these complex relations is to frankly classify the Nordic CWC phenomenon, especially BAC, as economically and culturally a hybrid society consisting of sedentary territorial pastoralists enrolled in seasonal movement related to herding practices (transhumance). Such circumstances could include raiding neighboring groups for cattle and other resources on a regular basis (cf. Evans-Pritchard 1940; Gray et al. 2003). Ethnographic studies of the Turkana pastoralists in NW Kenya provide insights in the highly violent communities of present-day pastoralists; males are extremely competitive and violent, and raids and retaliations are common (Harrod et al. 2012). There are likewise several examples of CWC violence in what is present-day Germany (e.g. Lidke 2005; Meyer et al. 2009) in addition to other places in Europe including Southern Scandinavia (e.g. Tornberg & Jacobsson 2018; Egjford et al. 2021; Fibiger et al. 2023). To judge from the frequent occurrence of skeletal trauma, Southern Scandinavia experienced increased levels of violence particularly during the CWC period (Tornberg et al. forthcoming). All these proxies in combination point to Nordic CWC as a quite unstable social and economic construct which was indeed substantially different from prior FBC 'Farmers' and subsequent sedentary LN agriculturalists. Intriguingly, all this traces back to the substantial biocultural transformations which began c. 2900 BCE and which were somehow reiterated c. 2600 BCE with a string of regionalisations. Hence, the volatile European 3rd millennium consolidated only in the last centuries when Late Neolithic societies appeared on the scene. Despite their name, they belonged to the European Early Bronze Age and, thus, to a new world order defined by bronze.

Conclusions

We performed high spatial resolution strontium isotope analysis of 70 individuals from Corded Ware Complex and megalithic passage graves from Scania, southernmost Sweden, and eastern Denmark, eastern Denmark, to evaluate mobility in the 3rd millennium BCE. The spatially resolved strontium isotope analysis suggests that there were high levels of mobility within the local surroundings, plausibly related to subsistence practices in an agropastoral community with high levels of territorialism. Demographic data from the Nordic CWC supports a substantial population increase as well as high levels of intercommunity contact and/or violence. Our strontium data confirms a significantly higher rate of mobility in the late Middle Neolithic, which is associated with the Nordic Corded Ware phenomenon, than in the Late Neolithic. We did not observe any obvious gender difference in mobility patterns or mobility patterns that could clearly be associated with violence and warfare. However, the individuals whose strontium data suggested moves over the longest distances all suffered from violence related trauma. The homogenous baseline values in some subareas might somewhat mask local mobility and differences in mobility associated with sex. An older adult female from Vellinge in southwestern Scania might provide support for mobility related to marital practices. Being of non-local origin, the last sequential strontium value was in accordance with the local environment where she was later buried. The equivalent age for this value is expected to be in late adolescence and may well be connected to relocation to a new household in a patrilocal exogamous society.

[Supplementary information](#)

Supplementary file 1: Sample overview

Supplementary file 2: Laser ablation measures and technical information

642 Supplementary file 3: Radiocarbon dates from Danish megaliths.

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