Mobility and diet in Prehistoric Denmark: strontium isotope analysis and incremental stable isotope analysis of human remains from the Limfjord area

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ABSTRACT
The Limfjord in Denmark held a prominent position throughout Prehistory as a natural communication port between east and west. Identifying the presence of non-local individuals might shed light on socio-economic and cultural changes occurring in the Limfjord area. Existing studies attempting to do so using strontium isotope analysis on Danish prehistoric remains focus on certain archaeological time periods and/or geographic locations, resulting in an uneven distribution of analysed material. This study aimed at filling a gap in the existing literature, both from a geographical as well as a chronological point of view. Additionally, carbon and nitrogen stable isotope analysis on bone and tooth dentine from these individuals was carried out to examine dietary changes between childhood and adulthood. The strontium isotope results revealed that three, potentially four, out of 27 individuals fall outside the "local" bioavailable baseline range; two from the Neolithic, one from the Early Roman Iron Age and one from the Germanic Iron/Viking Age. We conducted incremental stable isotope analysis of tooth dentine from the three, potentially four, non-local individuals to investigate the palaeodietary information in their dental records at a higher resolution and potentially pinpoint their age at the time of movement. The two Neolithic individuals revealed stable isotope ratios that might be indicative of stress.

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1. Introduction

The geographical setting of the Limfjord area in the northern part of the Jutland peninsula (Figure 1) by and near the sea as well as a natural communication port between east and west, has made this area one of Denmark's important nodal points for long distance communication and trade (Kristiansen 1987; 1998; Birkedahl and Johansen 2000; Kristiansen and Larsson 2005; Nielsen 2011). This has been the case since the Ertebølle culture when people lived as hunter-gather-fishers, leaving behind the famous kitchen middens (Andersen 2008), to the Bronze Age when a concentration of mounds and grave goods show the importance of the area (Bech 2003), to the Viking Age sites of Sebbersund as ports of trade (Price et al., 2012) as well as the circular fortresses of Fyrkat and Aggersborg constructed during the reign of Harald Bluetooth (Roesdahl 2008). See Figure 2 for an overview of the archaeological time periods.

As a nodal communication port, Limfjord's social and economic changes through time may be related to human mobility and consequently to contact with other cultures. Recently, ancient DNA analyses have revealed several large scale migrations in Europe during the Neolithic, as well as during the Late Neolithic/Early Bronze Age transition (Haak et al., 2015; Allentoft et al., 2015). In Scandinavia, recent investigations also address aspects of palaeomobility in Prehistoric Scandinavia from the Mesolithic to the Viking Age e.g. (Sjögren et al., 2009; Frei et al., 2015a; Frei et al., 2015b; Price et al., 2011; Harvig et al., 2014; Bergerbrant et al., 2017; Eriksson et al.,

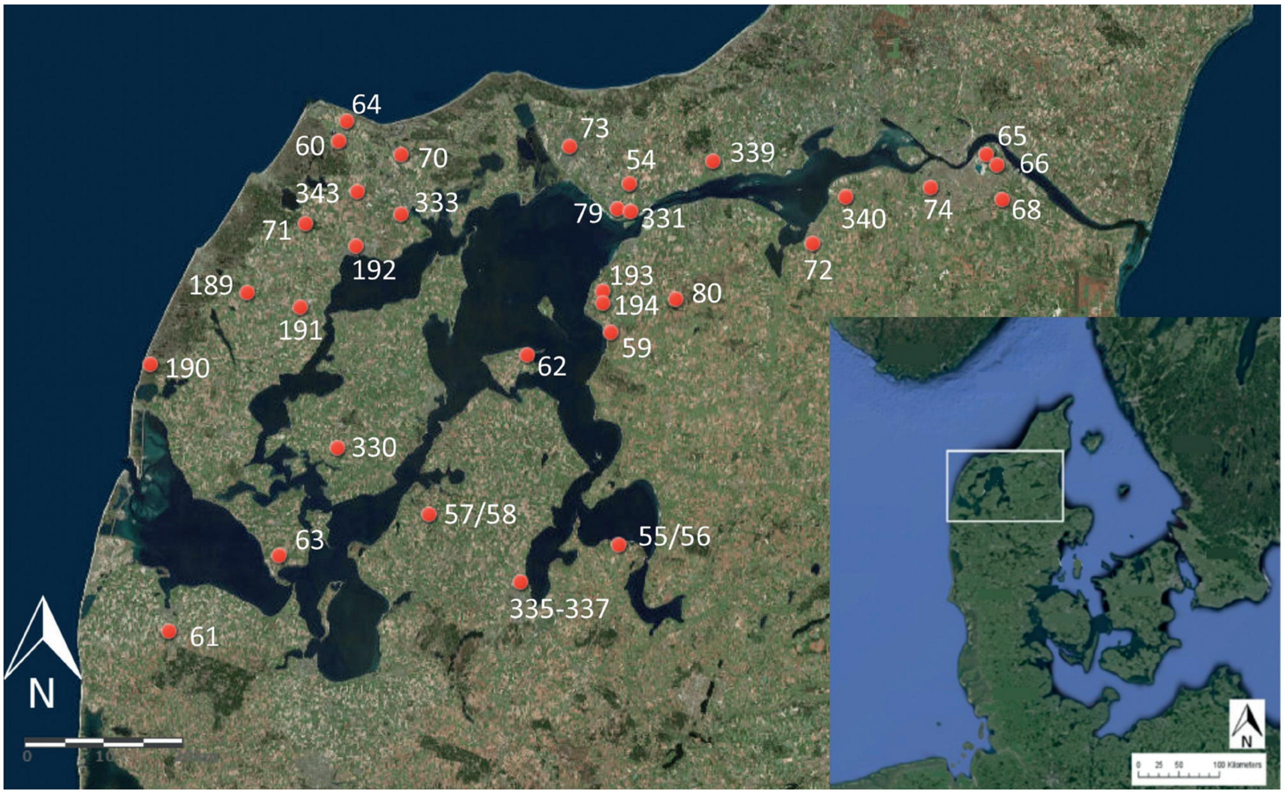

Figure 1. ArcGIS map with the sample numbers used in this study from the Limfjord area. The location of the Limfjord in Denmark is displayed in the inset. Used with permission (Copyright © 2017 Esri, ArcGIS Online, and the GIS User Community. All rights reserved).

2018; Frei et al., 2019). From within Scandinavia, Denmark has yielded the highest number of strontium isotope investigations. However, as in many other areas, the current literature does not equally represent all prehistoric periods. In Denmark, the two periods that seem to be mostly represented are the Bronze Age and the Viking Age.

In this paper we will attempt to identify migrants using strontium isotope analysis on human remains from the Limfjord area. This study aims to contribute to filling in this gap in Danish strontium isotope studies in two ways:

1) by providing new strontium isotope data from the Limfjord area –an area that has not yet been much investigated-, and

2) by providing strontium isotope data from various prehistoric periods, thus filling a chronological gap.

cal AD 800-1050	Viking Age (VK)
cal AD 400-800	Germanic Iron Age (GER)
0 cal BC/AD–cal AD 400	Roman Iron Age (RIA)
500 cal BC–0 cal BC/AD	Pre-Roman Iron Age (PRIA)
1000-500 cal BC	Late Bronze age (LBA)
1700-1000 cal BC	Early Bronze Age (EBA)
2400-1700 cal BC	Late Neolithic (LN)
2800-2400 cal BC	Middle Neolithic B (SGK)
3300-2800 cal BC	Middle Neolithic A (MN)
3900-3300 cal BC	Early Neolithic (EN)
5400-3900 cal BC	Late Neolithic – Ertebølle (ERT)

Figure 2. Timetable of Danish prehistoric periods.

Besides measuring strontium isotopes in human enamel, we measured strontium concentrations with the aim to discuss its potential value as an additional proxy. Additionally, the combination of strontium isotope analysis on the tooth enamel and carbon and nitrogen stable isotope analysis on the tooth dentine from the same tooth is also discussed. Finally, we performed incremental dentine carbon and nitrogen stable isotope analysis on a selection of teeth to investigate dietary changes during childhood and examine if a change in residency of an individual could potentially be linked to a change in diet from which the age of the movement could be deduced.

2. Movement of people in Danish prehistory

During the Neolithic small groups of people or individuals with farming skills have been assumed to have migrated into Denmark, probably spreading their knowledge to the local population (Sørensen and Karg 2014). The difference in pottery technique (Jensen 2013), the discrepancy between Scandinavia's wild aurochs and domesticated cattle (Noe-Nygaard and Hede 2006) and the relatively fast adoption of farming during the Neolithic all seem to suggest that migrants played an important role in the Mesolithic-Neolithic transition in Scandinavia. This is supported by ancient DNA studies, which reveal that Scandinavian farmers shared a closer genetic affinity with Central European farmers than with Mesolithic hunter-gatherers (Malmström et al., 2009; 2015). Additionally, numerous Bell Beaker potteries from the Late Neolithic period have been found around Limfjord, suggesting the existence of connections with Bell Beaker groups in central Europe (Arthursson 2015). These connections potentially enabled metal to be circulated to the North. Strontium isotope analyses also showed that Bell Beaker individuals from central Europe had a high degree of mobility (Price et al., 2004). However, recent investigations suggest that the distribution of Bell Beaker communities was spread out over Europe in seemingly isolated islands, although similarities in their material culture suggest that a degree of human mobility was involved (Vander Linden 2015). More recently, Frei et al. (2019) analysed strontium isotope ratios on human remains of 88 individuals from Denmark in order to investigate the degree of mobility across the Neolithic-Bronze Age transition. Four of these 88 individuals with radiocarbon ages dating to the Neolithic were excavated from the Limfjord area (2x Sejerslev, Dommergården and Sebber skole). Their strontium isotope ratios fall within the "local" baseline range for present-day Denmark.

During the Bronze Age the emergence of a supra-regional network which connected faraway regions, is evident in southern Scandinavia and northern Germany (Price et al., 2017; Bergerbrant et al., 2017; Frei et al., 2015a; Frei et al., 2017; Frei et al., 2019). During this period, mobility seems to have involved warriors (Price et al., 2017), commoners (Bergerbrant et al., 2017) and even elite females (Frei et al., 2015a; Frei et al., 2017). Due to the emergence of a social elite and the development of chieftains who presumably controlled the trade, warriors might have become indispensable for the protection and regulation of such a complex network (e.g. Kristiansen and Earle 2015). The Danish Jutland peninsula, in which Limfjord is situated, obtained a prominent position in the trading network from around the beginning of the Early Bronze Age (between 1700-1600 BC) onwards, probably due to the trade of metal and amber (Kristiansen 1987; Kristiansen and Larsson 2005; Nørgaard et al., 2019). Human mobility during the Nordic Bronze Age has also been illustrated by Frei et al. (2019) who observed a change in human mobility patterns from around 1600 BC. This change, which seems to have occurred during the transition period at the beginning of the Nordic Bronze Age, a time when society flourished, expanded and experienced an unprecedented economic growth, suggests that trade and human mobility might have been closely related. Two (Jestrup, and Øster Herup) out of 14 Bronze Age individuals analysed from the Limfjord area yielded non-local Sr isotopic signatures (Frei et al., 2019).

After the collapse of the interregional trading network and the associated hierarchical society at the end of the Bronze Age, the Pre-Roman Iron Age in Scandinavia seems to become more egalitarian (Myhre 2003). This is evident from cremation burials which at this time appear to be uniform and without rich furnishings (Sellevold et al., 1984; Myhre 2003). Additionally, this period reveals an intensification of the farming system in the form of Celtic fields, which enabled more reliable crop rotation systems. Overexploitation of resources towards the end of the Bronze Age provided an opportunity for technological innovations, which were essential during the Iron Age; farming became possible on heavy soils, while iron could be extracted locally in many places in Denmark, giving the local communities more independence and reducing their need for long-distance trade (Kristiansen 2010). The focus on locally available metal raw materials and the collapse of the Bronze Age network would suggest that people were less mobile during the Pre-Roman Iron Age compared to the previous period.

The Roman Iron Age was characterised by a re-opening up and increasing contact between Germanic tribes and Romans, resulting in trading and raiding activities. Defensive mechanisms, i.e., earthworks and fortifications, were constructed throughout the landscape in an attempt to withstand invasions (Kaul 1997, 2003; Jensen 2013). Archaeological evidence suggests several attacks against southern Scandinavia occurred, coinciding with the deposition of substantial offerings of weapons and riding gear (Ilkjær 2000). The chiefdom-oriented society that emerged during the Late Roman period continued into the Germanic Iron Age (Hall 2007). In addition to raids and attacks, market towns emerged in the 8th century and offered people the opportunity to gain personal wealth for maintaining prestige and securing alliances with other military leaders (Hall 2007).

The Viking Age is well known for its colonisations and long distance travel (Hall 2007). Market places developed into small towns with administrative, religious and legal activities in addition to trading and commerce (Hall 2007; Skre 2008; Jensen 2013; Price 2015; Ashby et al., 2015). In Denmark, several Viking Age sites have been investigated using strontium isotopic analyses of human remains, including the Limfjord site of Sebbersund, where three out of 19 analysed individuals have been identified as non-local (Price et al., 2012). However, this site has yielded more than 700 individuals, hence it is not possible at this point to estimate the percentage of non-locals vs. locals at this site.

At the Viking Age site of Galgedil on the island of Funen, tooth enamel samples from 36 humans yielded non-local Sr isotope values, which is about a third of the dataset (Price et al., 2015). Finally, Sr isotopic data from the famous fortress of King Harald Bluetooth, Trelleborg on the island of Zealand, indicated an even higher number of non-locals (Price et al., 2011; Frei et al., 2014).

3. Strontium isotope analysis

Strontium isotope analysis has proven to be a useful tool in identifying non-local individuals within the Scandinavian realm (Sjögren et al., 2009; Frei et al., 2015a; 2015b; Price et al., 2015; 2017; Bergerbrant et al., 2017; Frei et al., 2019). Geographical movements can be identified by comparing $^{87}Sr/^{86}Sr$ isotope ratios from tooth enamel with the local bioavailable $^{87}Sr/^{86}Sr$ isotopic range, which relates to the underlying geology (Ericson 1985; Price et al., 2002; Bentley 2006; Frei et al., 2020). After strontium is taken up into the human body through food and drinking water, it is incorporated into the mineral lattice of hydroxyapatite by substituting for calcium (Bentley 2006; Katzenberg 2008). However, a migrant will only become visible if the recorded $^{87}Sr/^{86}Sr$ ratio in human tissues deviates sufficiently from the local $^{87}Sr/^{86}Sr$ isotopic range. An individual travelling between two or more regions with the similar $^{87}Sr/^{86}Sr$ ranges might appear to be local. Similarly, a young individual whose tooth enamel is still forming, travelling across regions with varying $^{87}Sr/^{86}Sr$ ranges will present an average value of all of these strontium sources. Additionally, large and continuous marine food consumption during childhood can affect the tooth enamel $^{87}Sr/^{86}Sr$ values, pulling them towards the marine isotopic signal (Price and Naumann 2015). As the modern sea water $^{87}Sr/^{86}Sr$ signal falls within the Danish $^{87}Sr/^{86}Sr$ baseline, these individuals would appear local while they might not be, providing a conservative number of migrants in the dataset.

3.1 Diagenesis

Due to the high mineral content (Fitzgerald and Rose 2008), increased crystallographic organisation, crystal size and extremely low porosity, tooth enamel is less susceptible to diagenesis than dentine (Bentley 2006). Dentine is similar to bone in terms of composition and crystal size, although it is less porous than bone (Hillson 2005; Koch 2007; Burton 2008). Diagenesis should be taken into consideration when dealing with Sr isotopic data from dentine. Uptake of Sr from the burial environment including soil pore fluids by relatively porous dentine would likely result in convergence of the dentine Sr isotopic composition towards the values in the soil, assuming that the latter acts as an infinite reservoir.

3.2 Geology and Sr isotope geochemistry of Denmark

Compared to northern Scandinavian countries, Denmark is geologically relatively young. The geological bedrock consists among others of Late Cretaceous/Early Cenozoic carbonate rocks and marine clastic sediments, while the surface is overlain by glaciogenic sediments containing weathered Precambrian material originating from Norway and Sweden (Frei and Frei 2011; Frei and Price 2012). The Danish soil surface is composed of glacially transported reworked basement material and local deposited sediments (Frei and Price 2012; Houmark-Nielsen and Kjær 2003). While the limestone ranges in $^{87}Sr/^{86}Sr$ values between 0.7078 and 0.7082, the glaciogenic tills have more radiogenic values ($^{87}Sr/^{86}Sr$ >~ 0.7095) (Frei and Frei 2011). The Limfjord region is characterised predominant by Upper Cretaceous to Lower Tertiary carbonates with outcrops of Eocene and Oligocene volcanic ash layers. Both types of lithologies exhibit unradiogenic strontium isotopic values which seem to have influenced the $^{87}Sr/^{86}Sr$ ratios of local surface waters (Frei and Frei 2011). The bioavailable strontium isotopic range of present-day Denmark ($^{87}Sr/^{86}Sr$ = 0.7081 - 0.7111; excluding the Danish island of Bornholm, southeast of Sweden) was originally estimated from analysis of surface waters (Frei 2013; Frei and Frei 2011). These data have since been supplemented by analyses of environmental samples including soil extracts, plants, surface waters and fauna samples (e.g. Hoogewerff et al., 2019, Frei et al., 2017, Price et al., 2012, Price et al., 2011; Reiter et al., 2019; Frei et al., 2020), which have confirmed the range based on the surface waters alone.

4. Carbon and nitrogen stable isotope analysis

Carbon and nitrogen stable isotope data are commonly used in palaeodietary studies. For both carbon and nitrogen, uptake of the heavier isotopes increases with trophic level, ~1 ‰ for $\delta^{13}C$ (DeNiro and Epstein 1978) and ~3 ‰ for $\delta^{15}N$ (DeNiro and Epstein 1981), although higher enrichments have also been reported (~3-4‰) (Hedges and Reynard 2007). $\delta^{13}C$ values are useful in differentiating between terrestrial C3 plants (Smith and Epstein 1971; Price et al., 1985) and marine vegetation (DeNiro and Epstein 1978) in Prehistoric Denmark. A nursing effect can raise $\delta^{15}N$ values in breastfeeding children (Fogel et al., 1989; Richards et al., 2002). Stable isotope analysis performed on adult human bone gives an indication of the consumed diet of an individual's last years in life (depending on the bone element and its related remodelling time (Cox and Sealy 1997; Jørkov et al., 2009) prior to death. Because tooth enamel and the primary dentine are formed during childhood and do not remodel after formation, these tissues record and preserve isotopic information from childhood (Piesco 2002; Garg and Garg 2013; Nanci 2013), making them exceptionally suitable for studies involving migration. While the strontium isotope analysis of the tooth mineral can reveal a potential change in residency, the corresponding tooth dentine can provide information about the diet during childhood and changes therein.

5. Material

Tooth enamel and bones samples were selected based on preservation and availability, from a larger set of human and faunal samples collected from Danish museums for a large-scale palaeodietary study (van der Sluis 2017). As such, the locations of the tooth enamel samples in this study are spread around the Limfjord area, both in a geographical as well as in a chronological sense. The current dataset is largely composed of single finds originating from the Neolithic to the Viking Age. In total 27 human (Table 1) and 9 faunal (Table 2) tooth samples from the Limfjord in Denmark were analysed. All human teeth had fully developed roots, characterised by apical closure, except for two samples, Øslev (Lim-ht-054) and Romb (Lim-ht-061). The latter had incomplete roots, which were finished to stage R ¾, indicating an age of

Tooth sample number	Tooth code	Location	Bone sample number	Bone element	Sex/age	Museum number	AS_ID and/or grave number	Archaeological period	Remarks
Lim-ht-054	7-	Øslev	Lim-hb-095	femur fragment		ÅHM 1128/59	23/60	Single Neolithic	
Lim-ht-055	7-	Torsholm	Lim-hb-049	mandible (powder)	juvenile	NM A38203	Individual A	Neolithic	
Lim-ht-056	-7	Torsholm	Lim-hb-048	mandible (powder)	juvenile 16-17 years	NM A38203	Individual B	Neolithic	
Lim-ht-057	5	Krejbjerg og Ginderup	Lim-hb-044	mandible		NM A26287-99	Individual 1	Early/Middle Neolithic	
Lim-ht-058	5+	Krejbjerg og Ginderup	Lim-hb-045	cranium (powder)		NM A26287-99	Individual 2	Neolithic	
Lim-ht-059	-6	Bjørnsholm (Vitskøl)	Lim-hb-004	long bone fragment		NM 1107/57	08/58	Middle Neolithic/SGK	
Lim-ht-062	6+	Færkerhede	Lim-hb-005	humerus	female? 18-20 years	NM 512/55	18/81	Late Neolithic	M3 was erupting
Lim-ht-190	4+	Lodbjerg klit	Lim-hb-146	cranium	female? adult	THY 6165	x1	Early Middle Neolithic	only enamel
Lim-ht-191	7	Møgelvang	Lim-hb-148	cranium		THY 2151	x300	Neolithic	
Lim-ht-192	-6	Højvang Mark	Lim-hb-153	femur		THY 1098	x19	Single Neolithic	
Lim-ht-193	7+	Næsby Østergård	Lim-hb-182	cranium fragments	20-25 years	VMÅ 2251	x8 grave A2	Late Neolithic	only enamel
Lim-ht-060	6-	Nørtorp	Lim-hb-024	humerus	male 40-50 years	NM 909/59	4/59 skeleton #1	Early Bronze Age	
Lim-ht-063	+6	Følhøj	Lim-hb-042	mandible (powder)	18-21 years	NM B10830-32		Early Bronze Age	M3 was erupting
Lim-ht-064	-8	Rærgård	x		female 30-40 years	NM 576/12 B9653-54		Early Bronze Age	Only tooth, no bone
Lim-ht-189	6	Nørhå	Lim-hb-138	fibula	female 18-35 years	THY 1550	x13 (bone) x13B1 (tooth)	Early Bronze Age	
Lim-ht-065	4	Nørre Tranders Præstegård	Lim-hb-107	femur	male adult	ÅHM 42/55	skeleton 1	Early Roman Iron Age	
Lim-ht-066	6-	Nørre Tranders grusgrav	Lim-hb-112	tibia	female 55-60 years	ÅHM 16/58	Grave 5	Early Roman Iron Age	very mature
Lim-ht-068	5+	Christianshøj (Romdrup)	Lim-hb-113	cranium fragment	male adult	ÅHM 20, 4578-81	45/55 skeleton 1	Early Roman Iron Age	underneath stone layer
Lim-ht-070	-7	Korsø	Lim-hb-019	cranium (powder)	adult male	NM 560/59	7/59 Grave III	Early Roman Iron Age	
Lim-ht-072	+6	Rygegård	Lim-hb-105	long bone fragment	male 30-50 years	ÅHM 1469x4	20/85	Early Roman Iron Age	
Lim-ht-071	-7	Vandet skole	Lim-hb-036	ulna	adult, possibly male	NM 925/59	3/60 Grave 1	Late Roman Iron Age	very rich grave
Lim-ht-073	-5	Klim	Lim-hb-017	femur	female adult	NM C27382-400, 1167/57	13/58	Late Roman Iron Age	very rich grave
Lim-ht-074	-5	Gammel Hasseris	Lim-hb-006	femur	female mature	NM 759/61	8-64 Grave 1	Late Roman Iron Age	rich grave
Lim-ht-061	+6	Romb	Lim-hb-031	cranium fragment	adult 20±2 years	NM B10706	Grave C	Germanic/Viking Age	
Lim-ht-079	4-	Aggersborg Kirke	Lim-hb-001	ulna	male 20-35 years	NM D1916/1977	13/81	Viking Age	1030 AD (^{14}C dated)
Lim-ht-080	-5	Brårup	Lim-hb-022	cranium fragment	male adult	NM C28826-29, 477/61-62	14/69 skeleton 1	Viking Age	
Lim-ht-081	7+	Sebbersund	Lim-hb-087	cranium fragment	female 18-35 years	ÅHM 2863	32/02 x398 F4676	Viking Age	F number (Price et al., 2012)
Lim-ht-194	7	Næsby	Lim-hb-187	rib fragments	probable female	VMÅ 867	Grave A124 box A x497 (bone) box V x1153 (tooth)	Viking Age	rich female chamber grave, only enamel

Table 1. Material obtained from human remains used in this study. The tooth code refers to the number of the tooth element counted from the first incisor (1-8), + refers to a maxillary and – to a mandibular element, while the side is indicated by whether the + or – stands on the left or right of the element number. For example, +4 refers to the left maxillary 1st premolar. Age and sex where identified was possible are as reported in the original reports. *Strontium isotope analysis was performed by Price et al. (2012) on the Sebbersund sample (Lim-ht-081). This sample was included here for measuring the $\delta^{13}C$ and $\delta^{15}N$ values of the bone and dentine collagen.

Tooth sample	Animal species	Location	Museum ID number	Archaeological period
Lim-at-330	Equus caballus	Kammerhøj ved Redsted	Mors museum	Viking Age
Lim-at-331	Microtis	Aggersborg	ZMK109/1948 x49/559	Viking Age
Lim-at-333	Mus sp.	Hov, Flintmine	ZMK115a/1957	Neolithic
Lim-at-335	Capreolus capreolus	Krabbesholm II	ZMK50/2000 A6325	early Neolithic
Lim-at-336	Cervus elaphus	Krabbesholm II	ZMK50/2000 4478	early Neolithic
Lim-at-337	Bos taurus	Krabbesholm II	ZMK50/2000 2879	early Neolithic
Lim-at-339	Cervus elaphus	Kokkedalsmark	ZMK64/1983 x15	Bronze Age
Lim-at-340	Microtis	Mellemholm	ZMK31/1979 x340	Pre-Roman Iron Age
Lim-at-343	Microtis	Smedegård	ZMK38/1993 x501	Iron Age

Table 2. Faunal material used in this study.

7 ± 0.5 years (Moorrees et al., 1963; AlQahtani et al., 2010). The roots of the tooth from Øslev were broken off, presenting roots up to formation stage of R ½, corresponding to an age of circa 10.5 ± 0.5 years of age (Moorrees et al., 1963; AlQahtani et al., 2010). Skeletal remains of 13 human individuals were subjected to radiocarbon dating (Appendix 2), which was performed on the bone collagen from same individual.

6. Method

Methods of strontium isotope analysis, carried out in two laboratories are described, as well as methods for bone and incremental dentine collagen extraction.

6.1 Strontium isotope analysis

Tooth enamel samples weighed between 1.35 to 31.82 mg, with the small faunal samples providing the smaller amounts of tooth enamel. Two samples were analysed in both laboratories to test for tooth enamel heterogeneity, which involved taking two different enamel pieces from the same tooth. Human tooth enamel of 12 individuals were analysed at the University of Copenhagen, Denmark. Tooth enamel samples were cleaned and cut using a diamond dental burr. Any remaining dentine was carefully removed with the dental burr. The drilling equipment was thoroughly cleaned between samples with weak HCl acid (Seastar). After placing samples in pre-cleaned and numbered 7 mL Teflon (Savillex™) beakers, 6 drops of 30 % H_2O_2 (Seastar) and 3 drops of 6N HCl (Seastar) were added. The Teflon beakers were placed on the hotplate to dissolve the samples (few minutes), after which the lids were removed and samples left to dry at 80 °C. Subsequently, the enamel samples were taken up in a few drops of 3N HNO_3 and loaded onto disposable 100 µl pipette tip extraction columns into which we fitted a frit which retained 0.2 mL stem volume of intensively pre-cleaned mesh 50-100 Sr-Spec™ (Eichrome Inc.) chromatographic resin. The elution recipe essentially followed that by Horwitz et al. (1992), albeit scaled to our needs in so far as strontium was eluted by deionised water and then the eluate placed on the hotplate at 80 °C until dry. Thermal Ionisation mass spectrometry (TIMS) was used to determine the Sr isotope ratios. Samples were dissolved in 2.5 µl of a Ta_2O_5-H_3PO_4-HF activator solution and directly loaded onto previously outgassed 99.98 % single rhenium filaments. Samples were measured at 1250-1300 °C in dynamic multi-collection mode on a VG Sector 54 IT mass spectrometer equipped with eight faraday detectors (Institute of Geosciences and Natural Resource Management, University of Copenhagen). Five nanogram loads of the NBS 987 Sr standard that we ran during the time of the project yielded $^{87}Sr/^{86}Sr$ = 0.710241 ± 0.000011 (n=5, 2σ).

The other strontium isotope measurements were analysed at the National Centre for Isotope Geochemistry (NCIG) at UCD School of Earth Sciences, University College Dublin, Ireland. In total 30 measurements were made at UCD, three of which were on dentine, the rest on enamel. Of these 27 enamel samples, two were repeats (Lim-ht-061 and Lim-ht-066) of the samples analysed in Copenhagen to test for tooth enamel heterogeneity. One sample was analysed twice at UCD due to its highly radiogenic isotopic value (Lim-ht-191). Three dentine samples were analysed to examine the potential effect of diagenetic alteration on the $^{87}Sr/^{86}Sr$ values.

To cut enamel and dentine samples and clean the surface, dremel tools were used, which were thoroughly cleaned with weak HCl acid and Milli-Q water between taking samples. Samples were weighed into pre-cleaned Savillex Teflon beakers, dissolved in 2.5 mL of 6M HCl (aq.) and placed on the hotplate at 100 °C for evaporation. Samples were subsequently dissolved in 1 mL of concentrated (69 %) HNO_3 to breakdown any organics and evaporated at 100 °C. Columns were prepared using pre-cleaned filter frits, which were cleaned in a sonic bath for 10 minutes and stored in 1M HNO_3, while the Sr resin (Eichrom 100-150 µm) was measured by volume (20 mm from the bottom frit, equal to 100 mg). Columns were cleaned using several acid washes of 1M and 8M HNO_3 to remove other trace elements, finishing with 1M HNO_3 for preconditioning. Samples were dissolved in 1 mL of 1M HNO_3, placed in centrifuge tubes and spun down at 5000 RPM for 30 minutes to remove any particulate matter that might otherwise block the resin. Samples were introduced to the columns, washed with 1M and 8M HNO_3 to remove other trace elements, after which strontium is collected in pre-cleaned Teflon beakers using 2 mL 0.05M HNO_3. Collected samples of strontium were evaporated on the hotplate at 100 °C, dissolved in 1 mL concentrated HNO_3 to remove any organics from the resin and evaporated again. Strontium samples were dissolved in 0.05M HNO_3 and loaded onto rhenium filaments after which a tantalum-based activator ($TaCl_5$) was added for analysis on the Triton (TIMS). The average blank at UCD contained less than 1 ng of strontium, indicating a negligible amount of strontium contamination in the lab. During the period when the Limfjord analyses were run at UCD, the SRM987 reference material yielded $^{87}Sr/^{86}Sr = 0.7102611 \pm 0.0000144$ (2σ, n = 19).

Although measurements of $^{87}Sr/^{86}Sr$ in the SRM987 reference material in both Copenhagen and Dublin fall within uncertainty of the nominal value, they deviate in opposite senses (-0.000009 ± 0.000011 in Copenhagen and +0.000011 ± 0.000014 in Dublin). Hence, all measurements reported in this study have been normalised to the nominal value, i.e., 0.710250. Based on the reproducibility of analyses of SRM987 (in both Copenhagen and Dublin), a global uncertainty of ±0.00001 (2 sigma) is used for all $^{87}Sr/^{86}Sr$ analyses reported in this study (Table 3).

Strontium aliquots were taken to determine the strontium concentrations (ppm) using the Neptune ICPMS. These aliquots were made up to ca. 3 % HNO_3, and centrifuged to remove any particulate matter that could block the nebuliser. Sr concentrations are accurate to ca. 10 % and were calibrated using dilutions of the Ionex Multi Element ICP standard Solution 8E (Neptune Tune-up solution).

6.2 Bone and incremental dentine collagen extraction (IRMS) and radiocarbon dating (AMS)

The bone collagen extraction protocol (Brock et al., 2010) is based on the Longin method (Longin 1971) with the inclusion of an ultrafiltration step (Brown et al., 1988; Bronk Ramsey et al., 2004). A detailed description of the protocol, used standards and standard error on measurements is given elsewhere (van der Sluis et al., 2018). Collagen extraction for incremental dentine analysis followed method 2 from Beaumont et al. (2013). Samples were analysed using the Thermo Delta V IRMS with Flash Elemental Analyzer at the ^{14}CHRONO Centre in Belfast. Collagen samples were combusted, graphitised and run in the NEC compact model 0.5MV AMS at the ^{14}CHRONO Centre in Belfast (Appendix 2).

7. Results

Strontium isotope and strontium concentration results are presented first followed by the tooth dentine, bone collagen and incremental dentine collagen results.

7.1 Strontium isotope results

In total $^{87}Sr/^{86}Sr$ ratios were measured in 36 tooth enamel samples, of which 27 were human samples and nine were fauna samples (Table 3). The stron-

Sample	Site name	Archaeological period	$^{87}Sr/^{86}Sr^1$	Sr (ppm)
Lim-ht-054	Øslev	Late Neolithic	0.70934	
Lim-ht-056	Torsholm-individual B	Early Neolithic	0.71023	
Lim-ht-059	Bjørnsholm Vitskøl	Neolithic	0.71013	
Lim-ht-060	Nørtorp #1	Early Bronze Age	0.70913	
Lim-ht-062	Færkæde AS 18/81	Late Neolithic	0.70931	
Lim-ht-063	Følhøj	Early Bronze Age	0.71004	
Lim-ht-064	Rærgård	Early Bronze Age	0.70998	
Lim-ht-065	Nørre Tranders Præstegård	Early Roman Iron Age	0.70907	
Lim-ht-070	Korsø	Early Roman Iron Age	0.71021	
Lim-ht-071	Vandetskole grav 1	Late Roman Iron Age	0.70958	
Lim-ht-061*	Romb	Germanic/Viking Age	0.71187	
Lim-ht-066*	Nørre Tranders SOR grusgrav Grav 5	Early Roman Iron Age	0.70883	
Lim-ht-061*	Romb	Germanic/Viking Age	0.71203	130
Lim-ht-066*	Nørre Tranders SOR grusgrav Grav 5	Early Roman Iron Age	0.70884	127
Lim-ht-055	Torsholm -individual A	Early Neolithic	0.70995	63
Lim-ht-057	Krejbjerg og Ginderup	E/M Neolithic	0.71137	101
Lim-ht-057d	Krejbjerg og Ginderup dentine	E/M Neolithic	0.71441	116
Lim-ht-058	Krejbjerg og Ginderup	SGK Neolithic	0.71100	90
Lim-ht-058d	Krejbjerg og Ginderup dentine	SGK Neolithic	0.71427	104
Lim-ht-068	Christianshøj (Romdrup)	Early Roman Iron Age	0.70826	41
Lim-ht-072	Rygegård	Early Roman Iron Age	0.71111	70
Lim-ht-073	Klim	Late Roman Iron Age	0.71095	67
Lim-ht-074	Gammel Hasseris	Late Roman Iron Age	0.70996	60
Lim-ht-079	Aggersborg Kirke	Viking Age	0.71074	69
Lim-ht-080	Braarup	Viking Age	0.71029	218
Lim-ht-189	Nørhå	Early Bronze Age	0.71045	67
Lim-ht-190	Lodbjerg klit	Neolithic	0.70983	63
Lim-ht-191*	Møgelvang	SGK Neolithic	0.71387	188
Lim-ht-191*	Møgelvang	SGK Neolithic	0.71383	122
Lim-ht-191d	Møgelvang dentine	SGK Neolithic	0.71123	218
Lim-ht-192	Højvang Mark	SGK Neolithic	0.70883	91
Lim-ht-193	Næsby Østergård	Late Neolithic	0.71003	156
Lim-ht-194	Næsby	Viking Age	0.71006	177
Lim-at-330	horse Kammerhøj ved Redsted	Viking Age	0.71042	446
Lim-at-331	vole Aggersborg	Viking Age	0.70909	398
Lim-at-333	mouse Hov, Flintmine	Neolithic	0.70828	260
Lim-at-335	deer Krabbesholm II	Early Neolithic	0.71069	303
Lim-at-336	deer Krabbesholm II	Early Neolithic	0.71080	209
Lim-at-337	cattle Krabbesholm II	Early Neolithic	0.70992	326
Lim-at-339	deer Kokkedalsmark	Bronze Age	0,71077	290
Lim-at-340	vole Mellemholm	Pre-Roman Iron Age	0.70841	478
Lim-at-343	vole Smedegård	Iron Age	0.70914	326

1: All analyses have been normalised to a 87Sr/86Sr value = 0.71025 for the SRM 987 reference material (see text).

*Samples analysed in CPH and UCD to test sample heterogeneity.

Table 3. $^{87}Sr/^{86}Sr$ ratios (TIMS) and strontium concentration (ICPMS) of human tooth enamel and dentine ("d" in the sample number) and animal tooth enamel samples. The first 12 samples were analysed at Copenhagen and lack the strontium concentration data.

tium isotope ratios from our samples of human remains range from 0.70826±0.00001 (Lim-ht-068 measured in tooth enamel) to 0.71441±0.00001 (Lim-ht-057d measured in dentine). Two samples were analysed in both laboratories to test for tooth enamel heterogeneity. Sample Lim-ht-066 produced a $^{87}Sr/^{86}Sr$ ratio of 0.70884 ± 0.00001 in UCD and 0.70883 ± 0.00001 in Copenhagen, showing no detectable heterogeneity within analytical reproducibility. However, some samples display varying degrees of heterogeneity. For example, sample Lim-ht-191 yielded $^{87}Sr/^{86}Sr$ values of 0.71387 ± 0.00001 and 0.71383 ± 0.00001 in UCD. This small difference is potentially due to tooth enamel heterogeneity, which is supported by their different Sr concentrations. Sample Lim-ht-061 yielded a slightly larger difference ranging from $^{87}Sr/^{86}Sr$ = 0.71203 ± 0.00001 in UCD to 0.71187 ± 0.00001 in Copenhagen, suggesting a larger sample heterogeneity. This difference could stem from intra-sample variability related to different areas in the tooth from which the enamel samples was taken, which could be linked to a change in diet or perhaps a change in residency. As human tooth enamel formation takes several years to complete (AlQahtani et al., 2010), enamel from the crown can produce a different strontium isotopic signal than enamel closer to the root, in case this individual was geographically mobile during the time of formation.

While sample Lim-ht-072 (Early Roman Iron Age) is very close to the boundary of the baseline, samples with more radiogenic values (Lim-ht-057 (Neolithic), Lim-ht-061 (Germanic/Viking Age) and Lim-ht-191 (Neolithic)) indicate non-local individuals (Figure 3). The voles and mouse display similar $^{87}Sr/^{86}Sr$ ratios, while the large herbivores show more radiogenic isotopic values (Figure 3), which is probably related to the difference in feeding behaviour. Still, all animals from this study display $^{87}Sr/^{86}Sr$ ratios that fall within the Danish baseline of $^{87}Sr/^{86}Sr$ = 0.7081 and 0.7111. As such, our $^{87}Sr/^{86}Sr$ ratios of the faunal samples correspond well with the existing Danish baseline. However, a recent publication aiming at proposing a standardisation of how to create bioavailable strontium isotope baselines, recommends not to use animals, as even mice have been shown not to be local (Grimstead et al., 2017). Hence these should still be considered with care.

Our faunal tooth enamel samples have relatively high strontium concentrations (209-478 ppm, Table 3) in keeping with the general pattern that, compared with carnivores, herbivores have higher Sr concentrations in their tissues because plants are rich in strontium while meat is low in strontium (Bocherens et al., 1994; Tuross et al., 1989; Montgomery 2010). Strontium concentration values between 50-300 ppm have been reported in modern

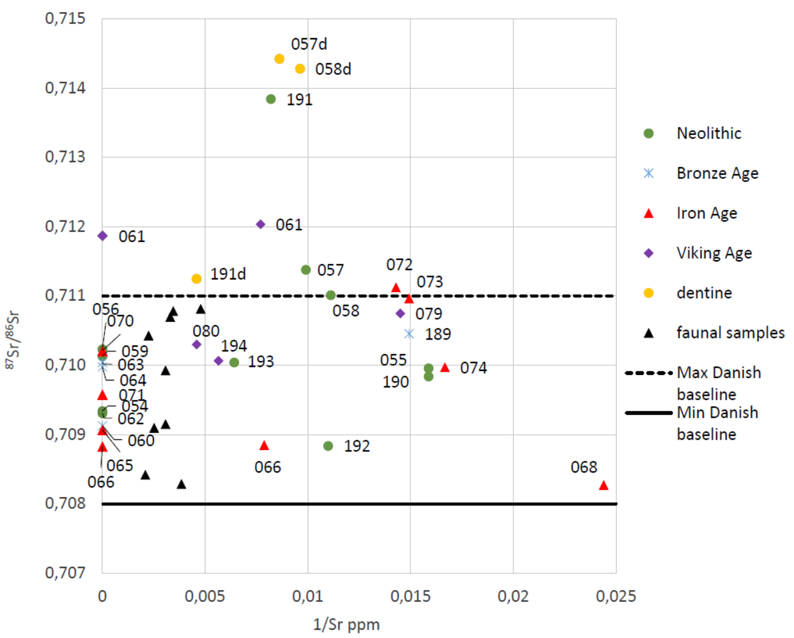

Figure 3. $^{87}Sr/^{86}Sr$ ratios and Sr concentrations of human and animal teeth from the Limfjord study. Samples displayed on the y-axis are the 12 samples lacking Sr concentration data and have been arbitrarily set to zero. $^{87}Sr/^{86}Sr$ ratios from samples Lim-ht-061 and Lim-ht-066 are plotted twice since two subsamples from each have been analysed. The area between the black lines represents the Danish baseline ($^{87}Sr/^{86}Sr$ = 0.7081 to 0.7111) (Frei and Frei 2011).

human skeletal and dental tissues (Brudevold and Söremark 1967; Elliott and Grime 1993; Hancock et al., 1989; Underwood 1977; Montgomery 2010) in keeping with our human tooth enamel data from the Limfjord (41-218 ppm, Table 3).

Three dentine samples were analysed to examine the potential effect of diagenetic alteration on the $^{87}Sr/^{86}Sr$ values. This is evident in sample Lim-ht-191 (Figure 4), whose enamel is much more radiogenic ($^{87}Sr/^{86}Sr$ = 0.71387) than its dentine ($^{87}Sr/^{86}Sr$ = 0.71123). However, the other two samples (lim-ht-057 and Lim-ht-058) show the opposite trend, i.e., their dentine is more radiogenic (Figure 4). There are several possible explanations for this. Firstly, as dentine represents a different formation period than enamel, the difference could potentially indicate mobility between the formation of these two tissues. Alternatively, the burial environment may have masked the original strontium values as a result of diagenesis. Finally, it can also be a combination of these factors.

The availability of Sr concentration data for most of the samples permits possible mixtures of Sr sources to be evaluated, at least qualitatively (Figure 5). Frei and Frei (2011) observed a mixing line in their surface water samples between a possibly pre-Quaternary limestone source (low $^{87}Sr/^{86}Sr$ ratios and high Sr concentration) and a source in glaciogenic soils, characterised by more radiogenic $^{87}Sr/^{86}Sr$ and low Sr concentration. Data in Figure 5 suggests a heterogeneous mixing scenario to explain the enamel and dentine data in our study. The pattern is similar to the one of Montgomery et al., (2007) for Neolithic and Bronze Age tooth enamel samples from England. In their study, Montgomery et al. (2007) suggest that this pattern is due to variable mixtures of more than two sources similar to data from the Neolithic individuals in the Yorkshire study of Montgomery et al., (2007). Two of the extreme end members in our study seem to be characterized by: 1) high Sr isotopic compositions and high Sr concentrations (low 1/Sr values); 2) intermediate Sr isotopic compositions and low Sr concentrations (higher 1/Sr values), indicated by respective trend arrows in figure 5. The third and common end member is characterized by low Sr isotopic compositions and high Sr concentrations which we equate with limestones also inferred by the study of Montgomery et al., (2007). This could indicate more than two endmembers are contributing strontium and/or that people were exploiting a variety of food sources.

7.2 Tooth dentine and bone collagen stable isotope results

One dentine increment from each tooth was analysed for its $\delta^{13}C$ and $\delta^{15}N$ ratios (Appendix 1).

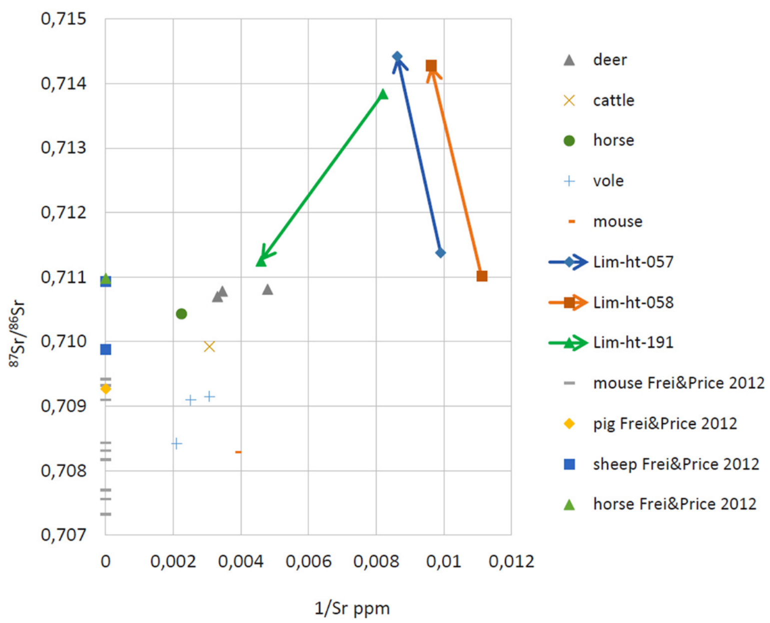

Figure 4. $^{87}Sr/^{86}Sr$ ratios and Sr concentrations of the faunal tooth enamel samples and human tooth dentine and corresponding enamel samples. The arrows point from the enamel to the dentine signal. Faunal samples from around the Limfjord area from Frei and Price (2012) have been added for comparison. Strontium concentrations are not available for these samples and have been arbitrarily set to zero.

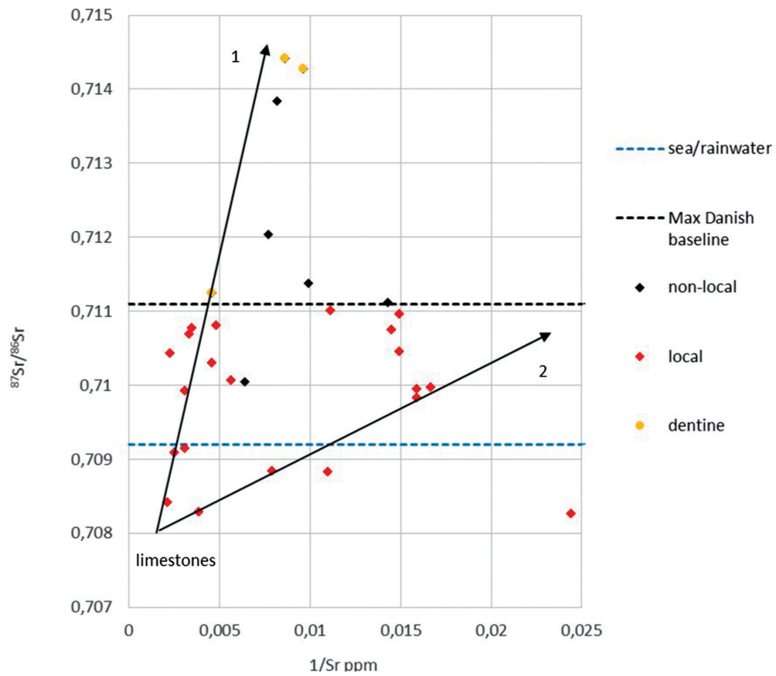

Figure 5. $^{87}Sr/^{86}Sr$ ratios and Sr concentrations of enamel and dentine samples analysed at UCD. The data array can be explained by contribution of strontium from three potential sources, each with their own strontium concentrations and strontium isotopic compositions. Trend arrows labelled 1 and 2 depict potential end-members of two of the sources, while limestones constitute the third source characterized by high strontium concentrations and low strontium isotopic signatures. Individuals interpreted as local are marked in red diamonds, while non-local individuals are plotted in black diamonds. Dentine values are plotted in yellow filled circles. Respective reference lines of the maximum Danish baseline (Frei and Frei, 2011) and modern sea water/rainwater are marked with black and blue dashed lines respectively.

Dentine increments selected for stable isotope analysis were taken from the roots rather than the crown to avoid the influence of a weaning signal. As such, the post-weaning early childhood diet can be compared with the adult dietary signal from the same individual. Increments of all 27 teeth yielded acceptable C:N ratios (DeNiro 1985), except for one sample, Øslev 5 (Lim-ht-054), which was excluded from further analyses. All dentine results have corresponding bone collagen results from the same individual, except for Rærgård (Lim-ht-064), for which no bone sample was obtained. No dentine was available from Lim-ht-193 and Lim-ht-194 and the corresponding bone samples failed to produce a signal on the IRMS. The change in diet is illustrated for each individual with an arrow from the childhood diet (represented by the dentine sample) to the adult diet (represented by the bone sample) (Figure 6). These changes in diet can be interesting when combined with strontium isotope analysis to investigate a person's geographic origin. Large shifts in diet between the childhood and adult life could indicate dietary changes related to different cultural practices or perhaps a change in residency.

Only changes in $\delta^{13}C$ and $\delta^{15}N$ ratios larger than 1‰ are discussed here. The Neolithic samples (Figure 6A) reveal four individuals with changes in at least one of their stable isotope ratios between adulthood and childhood. Sample Lim-ht-055 is the only Neolithic sample that shows a decrease in both stable isotope ratios (1.4 ‰ in $\delta^{13}C$, 1.2 in $\delta^{15}N$) from the childhood diet to the adult diet. Three other samples reveal a change in one of their stable isotopic ratios - a drop in the $\delta^{15}N$ ratios of 1.4 ‰ (Lim-ht-056), an increase in the $\delta^{15}N$ ratio of 1.5 ‰ (Lim-ht-191) and an increase in the $\delta^{13}C$ ratio of 1.1 ‰ (Lim-ht-057). The samples from the Bronze Age show little variation between the childhood and adult diets (Figure 6B), as do the samples from the Early Roman Iron Age (Figure 6C). The Late Roman Iron Age individuals seem to have different childhood diets but cluster around similar stable isotope ratios later in life, indicating a similar diet isotopically (Figure 6D). Sample Lim-ht-073 shows an increase in the $\delta^{13}C$ ratio of 1.1 ‰ combined with a decrease in the $\delta^{15}N$ ratio of 1.2 ‰ from the childhood diet to the adult diet. Sample Lim-ht-074 similarly reveals a drop in its $\delta^{15}N$ ratio of 1.5 ‰. Two Viking Age samples show a decrease in both stable isotope ratios from the childhood to adulthood (Figure 6E), in Lim-ht-061 (1.2 ‰ in $\delta^{13}C$, 1.1 in $\delta^{15}N$) and Lim-ht-081 (1 ‰ in $\delta^{13}C$, 1 ‰ in $\delta^{15}N$).

An increase in $\delta^{15}N$ ratios is visible from the Neolithic (8-10 ‰) to the Viking Age (~11-13 ‰), which is similarly visible in a large bone collagen stable isotope dataset from these prehistoric periods and can be interpreted as the increase of marine protein consumption combined with a potential manuring effect (van der Sluis 2017).

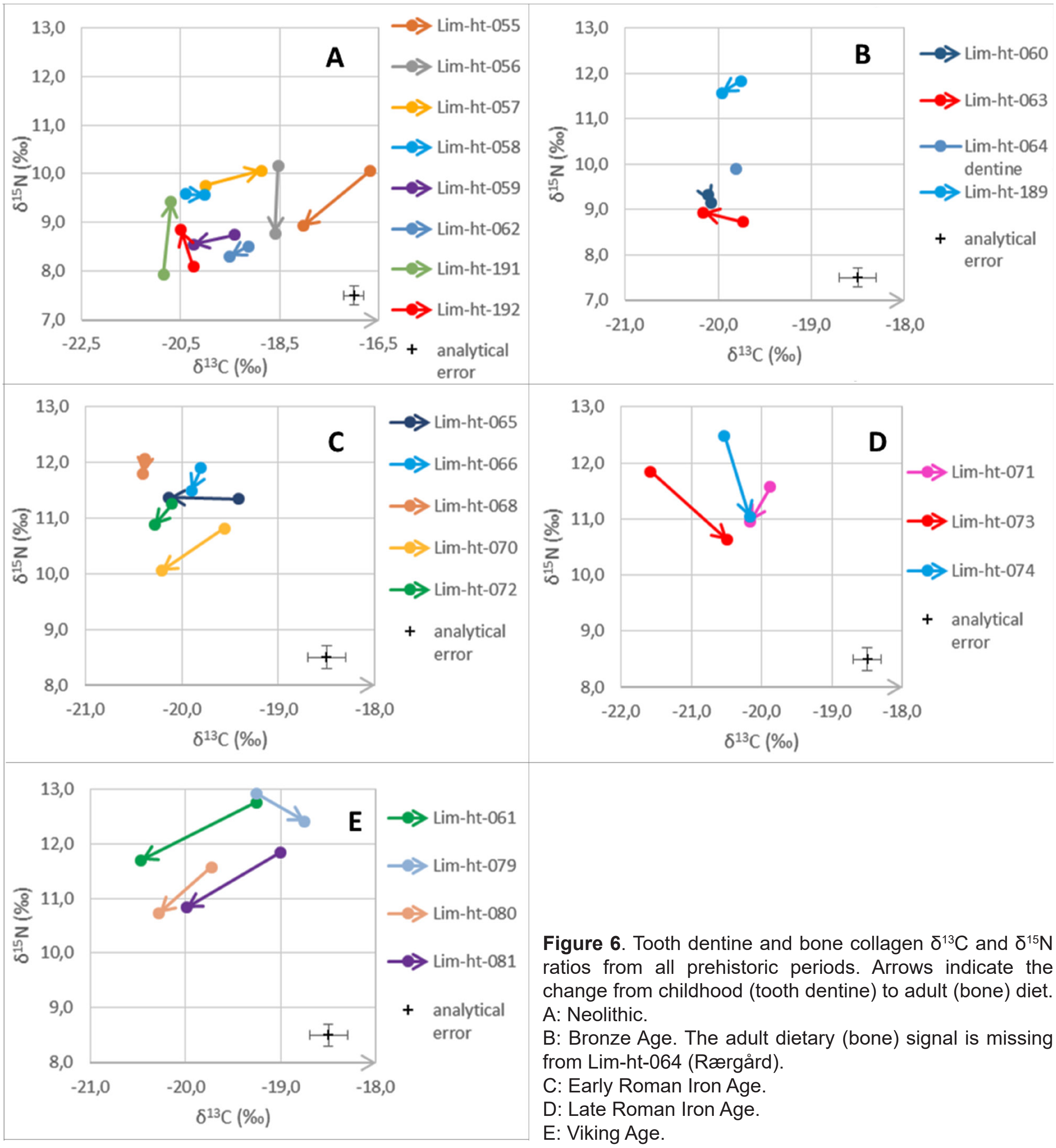

Figure 6. Tooth dentine and bone collagen $\delta^{13}C$ and $\delta^{15}N$ ratios from all prehistoric periods. Arrows indicate the change from childhood (tooth dentine) to adult (bone) diet.
A: Neolithic.
B: Bronze Age. The adult dietary (bone) signal is missing from Lim-ht-064 (Rærgård).
C: Early Roman Iron Age.
D: Late Roman Iron Age.
E: Viking Age.

Wider ranging $\delta^{13}C$ and $\delta^{15}N$ ratios are visible in Neolithic and Viking Age samples, while less variation is visible in samples from the Bronze Age and Roman Iron Age. The general trend in most time periods is one of decreasing $\delta^{13}C$ and $\delta^{15}N$ ratios from the dentine to the bone sample. While care was taken to avoid dentine increments likely to show a weaning effect, i.e. close to the crown, this cannot be ruled out completely as different weaning ages existed in different time periods. This decrease in $\delta^{13}C$ and $\delta^{15}N$ ratios most likely indicates different diets were consumed during the childhood and adulthood, possibly connected to cultural practices regulating which food sources were available at certain ages. It is interesting to see more elevated isotopic ratios in the dentine than in the corresponding bone samples, suggesting these individuals were feeding on a higher trophic level in their early childhood (post-weaning) than in the final years of their adult life.

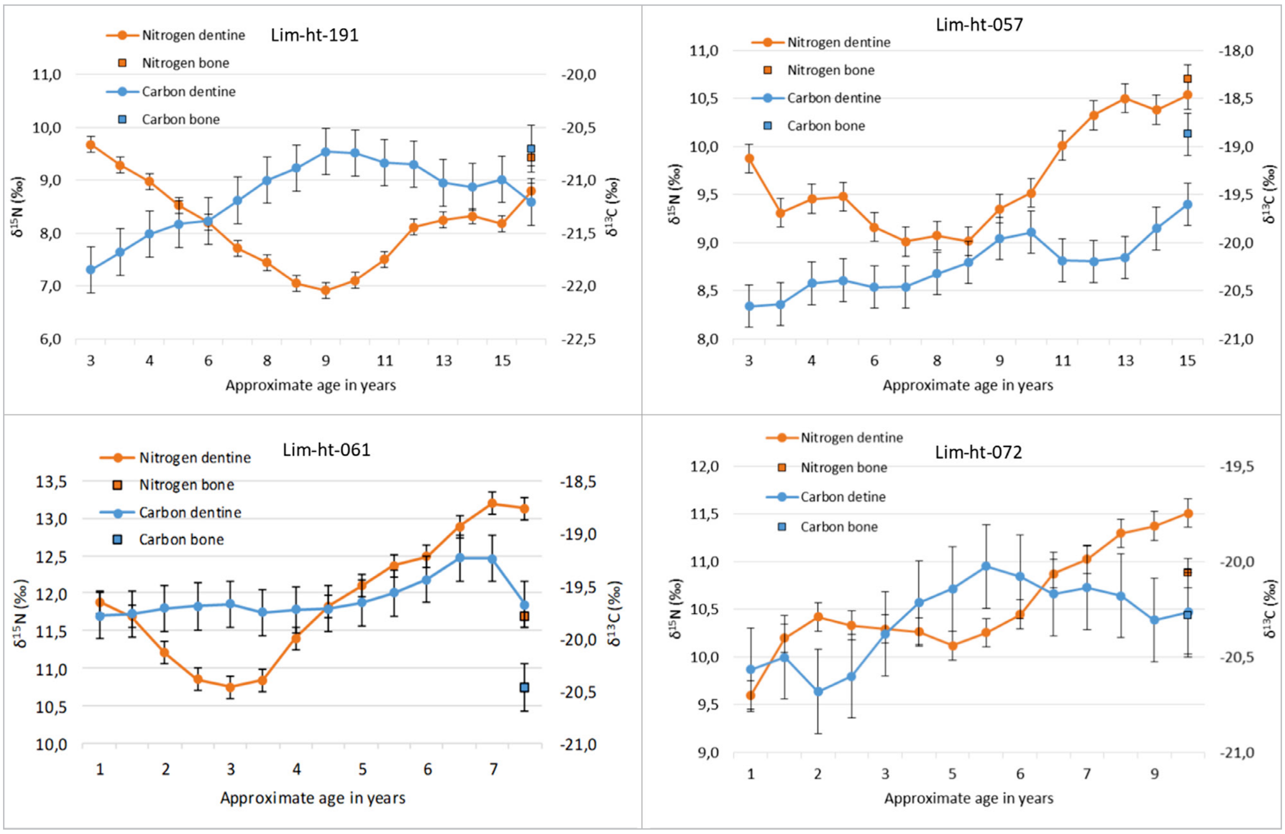

Figure 7. Incremental tooth dentine profiles of $\delta^{13}C$ and $\delta^{15}N$ ratios for the four non-local individuals. Bone collagen $\delta^{13}C$ and $\delta^{15}N$ ratios are displayed at the far right of each graph by a marker with a black outline.

7.3 Incremental dentine stable isotope results

Stable isotope analysis was performed on incremental tooth dentine sections from the 3, potentially 4, non-local individuals (Figure 7) to investigate their childhood diets and potentially connect this to their moment of movement. The two Neolithic teeth (Lim-ht-191 and Lim-ht-057) show a similar pattern with decreasing $\delta^{15}N$ ratios combined with rising $\delta^{13}C$ ratios from 3 to 8.5-9 years of age, after which $\delta^{15}N$ ratios start to rise combined with a slight decrease in $\delta^{13}C$ ratios. The decrease in $\delta^{15}N$ ratios in the early years could be related to the final phase of weaning, after which the child was most likely feeding on a low trophic level diet (e.g. porridge or gruel) with perhaps the addition of some low trophic level marine protein, considering the rise in $\delta^{13}C$ ratios. However, the isotopic changes are rather large in Lim-ht-191, with a drop of 2.7 ‰ in $\delta^{15}N$ ratios and a rise of 1.1 ‰ in $\delta^{13}C$ ratios. The second half of the Neolithic profiles is characterised by increasing $\delta^{15}N$ ratios, almost 2 ‰ in Lim-ht-191 and 1.5 ‰ in Lim-ht-057. In Lim-ht-191 the increase of almost 2 ‰ in $\delta^{15}N$ is combined with a drop of 0.5 ‰ in $\delta^{13}C$. The bone collagen $\delta^{13}C$ and $\delta^{15}N$ ratios in both individuals are higher than their final dentine increments.

Interesting to note are the very low $\delta^{13}C$ ratios (-21.8 ‰) in the early childhood of Lim-ht-191. It is possible that this individual lived in a forested environment before consuming different food types.

The profile of Lim-ht-061 starts with a drop in $\delta^{15}N$ ratios until the age of 3, possibly indicating a weaning remnant, followed by a rise of 2.5 ‰ in $\delta^{15}N$ ratios and an increase of 0.4 ‰ in $\delta^{13}C$ ratios. The co-variation between the two isotopic ratios would suggest diet as a factor for this shift, most likely the consumption of high trophic level marine protein. This individual is from the Germanic/Viking Age, a time period when the consumption of marine food sources is evident on a larger scale again (van der Sluis 2017). The bone collagen $\delta^{13}C$ and $\delta^{15}N$ ratios are considerably lower than the last dentine increment. If a change in residency can be associated with a change in stable isotope ratios, it seems plausible that this occurred after the age of 7 for this individual.

In Lim-ht-072 breastfeeding possibly continued until the age of 2, after which a slight decrease of 0.3‰ in $\delta^{15}N$ ratios and increase of 0.7 ‰ in $\delta^{13}C$ ratios is visible, followed by an elevation in $\delta^{15}N$ ratios of 1.25 ‰ and a drop in $\delta^{13}C$ ratios of 0.24 ‰ from 5-6 years of age, similar to the patterns visible in the profiles of Lim-ht-191 and Lim-ht-057 with rising $\delta^{15}N$ ratios and dropping $\delta^{13}C$ ratios.

When $\delta^{15}N$ and $\delta^{13}C$ values co-vary, a change in diet appears to be the underlying factor, which could be the result of certain cultural practices or a period of movement during which different foods were consumed. While co-varying $\delta^{13}C$ and $\delta^{15}N$ ratios indicate induced dietary changes, a rise in $\delta^{15}N$ ratios combined with a decrease in $\delta^{13}C$ ratios may signal nutritional stress (Neuberger et al., 2013; Beaumont et al., 2015; Beaumont and Montgomery 2016; Meier-Augenstein 2017). This pattern is visible in Lim-ht-191 between ages 9 and 15.5, where an increase of almost 2 ‰ in $\delta^{15}N$ is combined with a drop of 0.5 ‰ in $\delta^{13}C$ and could be linked to a nutritionally stressful phase in this individual's life, for example during prolonged illness.

However, before $\delta^{13}C$ and $\delta^{15}N$ ratios can be connected to potential moments of movement, more dentine profiles from individuals who are deemed local based on their strontium isotopic signature should be analysed to investigate their childhood diets and changes therein for comparison with the dentine profiles of these potentially four non-local individuals.

8. Who were these non-local individuals?

While the majority of the samples within our study revealed strontium isotopic values that fall within the local range, a few have non-local values. The Møgelvang sample (Lim-ht-191) has the most radiogenic value within our dataset of $^{87}Sr/^{86}Sr = 0.71387$ and indicates an origin outside present-day Denmark (excluding the island of Bornholm). Areas with such values can be found in, e.g., Sweden, Norway, the Danish island of Bornholm or central Europe (Nehlich et al., 2009; Frei and Frei 2013; Price and Naumann 2015; Wilhelmson and Price 2017).

At Møgelvang a ploughed over burial mound contained the remains of a long dolmen with NE-SW orientation from the Funnel Beaker Culture with two chambers. Although nearly all stones had been removed, marks in the ground, occasionally with remains of the stone itself, showed their original position. A battle axe from the Single Grave Culture originated from the dolmen and may have belonged to a secondary interment in one of the chambers. The southern chamber was trapezoidal and roughly oriented East-West, with the wider end in the west and a passage in the east. Along the northern side of this chamber was a disturbance, as stray objects from the Iron Age and younger periods were found here and in the holes from the removed stones. Bone material, amber beads, a small, ornamented vessel (Middle Neolithic I style) and flint blades were found inside the chamber. The stones used in the construction of the long dolmen seem to have been mostly granite, although flat chalk stones as pavement and flat stones made of Mo-Clay were also found (pers. comm Louise Haack-Olsen). The Mo-Clay consisting of diatoms, clay and ash layers, is typical for the Limfjord area in Denmark (Heilmann-Claussen and Surlyk 2006). A recent study from Frei et al. (2019) also included strontium isotope analyses of seven individuals from the Single Grave Culture burial site of Gjerrild in eastern Jutland. One individual, a female, yielded a value that falls outside the "local" baseline range ($^{87}Sr/^{86}Sr = 0.7127$, Rise 1283) and was also interpreted as non-local. The other six individuals yielded values that fall within the "local" baseline range of present-day Denmark (Frei et al., 2019).

Samples were taken from a cranium fragment and a molar found along the western end wall of the southern chamber close to a flint blade and to the small ornamented vessel, which, however, lay in a secondary position. The cranium was dated to 2901-2586 cal BC (Appendix 2), the Middle Neolithic A/Single Grave Culture. While the childhood dietary signal shows a terrestrial-based diet ($\delta^{13}C$ = -20.9 ‰) with a low $\delta^{15}N$ value (7.9 ‰), the adult diet shows a similar $\delta^{13}C$ value (-20.7 ‰) but higher $\delta^{15}N$ value (9.4 ‰) (Figure 7), signalling an increase of dietary protein.

The Romb tooth (Lim-ht-061) also yielded a relatively radiogenic Sr ($^{87}Sr/^{86}Sr = 0.71203$)

signal, indicating an origin outside present-day Denmark. Parts of the cranium of an adult individual of 20 ± 2 years of unknown sex were found in grave C. The burial was covered by a round mound, while other graves found in the vicinity were cremations. A bone sample from the cranium was radiocarbon dated to 675-867 cal AD (Appendix 2), i.e., the Germanic/Viking Age. While the childhood diet suggests some marine protein intake ($\delta^{13}C$ = -19.3 ‰ and $\delta^{15}N$ = 12.8 ‰), this is reduced in the adult diet ($\delta^{13}C$ = -20.5 ‰ and $\delta^{15}N$ = 11.7 ‰).

Krejbjerg og Ginderup (lim-ht-057) is derived from a Passage grave, which was constructed of eight upright stones and two cap-stones, with a passage towards the east. Artefacts found in the chamber consisted of three flint axes, blades, amber beads and parts of several skeletons. Artefacts date to the Funnel Beaker Culture and the Single Grave Culture. The site Krejbjerg og Ginderup had two boxes in the National Museum, one with a mandible and one with the cranium, which, based on the state of preservation and discolouration, appeared to belong to different individuals. Additionally, a partial maxilla is in the box with the mandible indicating a minimum of at least 2 individuals. The cranium and mandible were sampled for bone and teeth.

The non-local individual (Lim-ht-057) was radiocarbon dated to 3518-3123 cal BC (Appendix 2), Early/Middle Neolithic. This individual had a terrestrial-based diet ($\delta^{13}C$ = -20.0 ‰ and $\delta^{15}N$ = 9.8 ‰) during their childhood, while the adult diet shows an increase in the $\delta^{13}C$ ratio of 1 ‰, suggesting only a slight increase in marine protein intake ($\delta^{13}C$ = -18.9 ‰ and $\delta^{15}N$ = 10.1 ‰). The other individual (Lim-ht-058) was radiocarbon dated to 2866-2574 cal BC (Appendix 2), the Single Grave Culture, and had a $^{87}Sr/^{86}Sr$ ratio right on the boundary of the Danish baseline (0.7111) proving very difficult to assess if this individual is local or not. This person's childhood diet ($\delta^{13}C$ = -20.4 ‰ and $\delta^{15}N$ = 9.6 ‰) was isotopically similar to the older individual from the Passage grave, the adult diet ($\delta^{13}C$ = -20.0 ‰ and $\delta^{15}N$ = 9.6 ‰) does not show a shift.

Rygegård (lim-ht-072) yielded a $^{87}Sr/^{86}Sr$ ratio of 0.71111, which straddles the upper limit of the Danish baseline range. This renders it difficult to interpret the provenance of this individual solely on this datum. Cranial fragments, including parts of the mandible and maxilla, fragments of the femurs, ribs and teeth were preserved, indicating a 30-50 year old male individual was buried in a stone coffin grave from the Early Roman Iron Age. A dark feature in the yellow soil was found during field ploughing. In this feature an east-west oriented grave was encountered with upright flat stones against the walls, one on the east and west sides, two stones on the north and south sides. Covering stones were placed on top of these upright stones. A decorated pottery piece with an ear was found inside the eastern side of the grave, while cranial fragments were encountered in the western side of the grave. Traces of bones were present on the bottom of the grave. Fragments of ornamented pottery place this grave in the Early Roman Iron Age, which is confirmed by the radiocarbon date of cranium fragments, 85-232 cal BC. Isotopically, the childhood diet ($\delta^{13}C$ = -20.1 ‰ and $\delta^{15}N$ = 11.3 ‰) and adult diet ($\delta^{13}C$ = -20.3 ‰ and $\delta^{15}N$ = 10.9 ‰) are quite similar, indicating no dietary shifts.

Finally, there is an unusual type of burial that could hint at a non-local origin. The burial consisted of a flat inhumation grave with a stone frame contained skeletal remains of 3 individuals from the Early Roman Iron Age. Skeleton 1 belonged to an adult male individual and was positioned on the bottom of the grave with 2 clay pots and covered by a stone layer. Skeleton 2 was an adult individual with severe osteoarthritis found above the stone layer. Skeleton 3 belonged to an adult individual and was found during physical anthropological examination. Romdrup (Lim-ht-068) belonged to the adult male individual found under the stone layer. While this individual's $^{87}Sr/^{86}Sr$ ratio falls within the Danish baseline range, its low Sr concentration could suggest a non-local individual. A similar 'outlier' with low $^{87}Sr/^{86}Sr$ ratio and low strontium concentration has been pointed out by Montgomery (2010). His childhood and adult diet are very similar (childhood diet $\delta^{13}C$ = -20.4 ‰ and $\delta^{15}N$ = 12.1 ‰ adult diet $\delta^{13}C$ = -20.4 ‰ and $\delta^{15}N$ = 11.8 ‰), indicating no large dietary changes.

Three, potentially four, out of 27 individuals in this dataset have strontium isotope values that fall outside the local baseline range. Two of these individuals are from the Neolithic, one from the Early Roman Iron Age and one from the Germanic/Viking Age. While some degree of mobility was to be expected in the Germanic/Viking Age individuals based on the results of previous studies (Price et al., 2011; 2012; 2015; Frei et al., 2014), the non-local individuals from the Neolithic and Early Roman Iron Age provide additional insights into the degree of human mobility during those periods. Comparing the results from the present study to that of Frei et al. (2019), an interesting observation can be made. The two Neolithic individuals (Møgelvang sample Lim-ht-191 and Krejbjerg og Ginderup lim-ht-057) with non-local Sr signatures from this study were excavated in the vicinity of the individuals with non-local Sr signatures from Frei et al. (2019). Møgelvang is not far from Jestrup in Thy, while Krejbjerg og Ginderup is close to Øster Herup in Skive. While this may just be a simple coincidence, future strontium isotope research may shed light on potential mobility patterns in the Limfjord area and its surroundings.

9. Conclusion

Our study is the first to investigate mobility and diet of several individuals covering diachronic prehistoric periods in the Limfjord area, a key archaeological region in Denmark due to its geographical location easily accessible by waterways. Of the 27 individuals analysed in this dataset, the large majority yielded Sr isotope values that point to local origin. However, three, potentially four, individuals yielded strontium isotope ratios suggesting a geographic origin outside present-day Denmark (the island of Bornholm excluded). This study also provided strontium isotope concentration data of the Danish samples, which have not been published before and add useful information about the potential Danish strontium sources and their characteristics.

Dietary changes were investigated through stable isotope analysis of paired dentine and bone samples, as well as incremental dentine sections, which can shed light on the childhood diet and changes therein, although nutritional stress may also leave its markers in the stable isotope ratios. As travelling in the past may have been strenuous, longer periods of nutritional stress may be apparent in the $\delta^{13}C$ and $\delta^{15}N$ profiles. However, before this can be identified in the current non-local individuals, incremental dentine profiles of local individuals are needed for comparison.

This study provides new information about human mobility and diet from this key area in Denmark. However, the restricted sample size in relation to the large time scale covered by the samples prevent us, at this point, to draw broader conclusions. Nevertheless, the present study hopes to shed light on potential issues related to mobility.

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Appendix 1. Stable isotope results

Table 1. $\delta^{13}C$ and $\delta^{15}N$ ratios from human incremental dentine samples and corresponding bone samples.

Sample number	Sample name and Increment number	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)	C:N	Dentine yield (%)	Bone number	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)	Period
Lim-ht-054	Øslev 5	9.0	-21.5	4.0	62.7	Lim-hb-095	8.7	-20.4	SGK
Lim-ht-055	Torsholm A 12	10.1	-16.7	3.6	59.0	Lim-hb-049	8.9	-18.0	EN
Lim-ht-056	Torsholm B 10	10.2	-18.5	3.4	46.6	Lim-hb-048	8.8	-18.6	EN
Lim-ht-057	Krejbjerg og Ginderup 11	9.8	-20.0	3.2	29.2	Lim-hb-044	10.1	-18.9	EN/MN
Lim-ht-058	Krejbjerg og Ginderup 7	9.6	-20.4	3.2	36.3	Lim-hb-045	9.6	-20.0	SGK
Lim-ht-059	Bjørnsholm Vitskøl 17	8.8	-19.4	3.3	69.7	Lim-hb-004	8.6	-20.2	Neo
Lim-ht-062	Færkærhede 12	8.5	-19.1	3.2	22.2	Lim-hb-005	8.3	-19.5	LN
Lim-ht-191	Møgelvang 12	7.9	-20.9	3.2	46.9	Lim-hb-148	9.4	-20.7	SGK
Lim-ht-192	Højvang Mark 13	8.1	-20.2	3.2	83.2	Lim-hb-153	8.9	-20.5	SGK
Lim-ht-060	Nørtørp 15	9.3	-20.1	3.3	40.8	Lim-hb-024	9.2	-20.1	EBA
Lim-ht-063	Følhøj 19	8.7	-19.7	3.3	42.3	Lim-hb-042	8.9	-20.2	EBA
Lim-ht-064	Rærgård 10	9.9	-19.8	3.2	26.9	x			EBA
Lim-ht-189	Nørhå 11	11.8	-19.8	3.3	29.4	Lim-hb-138	11.6	-20.0	BA
Lim-ht-065	NørreTranders 12	11.4	-19.4	3.3	30.8	Lim-hb-107	11.4	-20.1	ERIA
Lim-ht-066	Nørre Tranders 13	11.9	-19.8	3.2	37.4	Lim-hb-112	11.5	-19.9	ERIA
Lim-ht-068	Romdrup 7	12.1	-20.4	3.3	28.8	Lim-hb-113	11.8	-20.4	ERIA
Lim-ht-070	Korsø 13	10.8	-19.6	3.3	33.8	Lim-hb-019	10.1	-20.2	ERIA
Lim-ht-072	Rygegård 12	11.3	-20.1	3.3	25.0	Lim-hb-105	10.9	-20.3	ERIA
Lim-ht-071	Vandet skole 11	11.6	-19.9	3.3	37.1	Lim-hb-036	11.0	-20.2	LRIA
Lim-ht-073	Klim 10	11.9	-21.6	3.7	17.5	Lim-hb-017	10.6	-20.5	LRIA
Lim-ht-074	Gammel Hasseris 18	12.5	-20.5	3.4	30.2	Lim-hb-006	11.0	-20.2	LRIA
Lim-ht-061	Romb 12	12.8	-19.3	3.2	43.9	Lim-hb-031	11.7	-20.5	GER/VK
Lim-ht-079	Aggersborg kirke 12	12.9	-19.3	3.4	23.3	Lim-hb-001	12.4	-18.8	VK
Lim-ht-080	Brårup 10	11.6	-19.7	3.2	38.9	Lim-hb-022	10.7	-20.3	VK
Lim-ht-081*	Sebbersund 11	11.8	-19.0	3.2	35.1	Lim-hb-087	10.8	-20.0	VK
Lim-ht-193	Næsby Østergård	x				Lim-hb-182	failed		LN
Lim-ht-194	Næsby	x				Lim-hb-187	failed		VK

* The tooth sample Lim-ht-081 (Sebbersund) produced a $^{87}Sr/^{86}Sr$ ratio of 0.71024 (Price et al., 2012).

Table 2. Incremental dentine stable isotope analysis of the 4 non-local individuals.

Sample	$\delta^{15}N$(‰)	$\delta^{13}C$ (‰)	C:N
Møgel1	9.7	-21.9	3.2
Møgel2	9.3	-21.7	3.2
Møgel3	9.0	-21.5	3.2
Møgel4	8.5	-21.4	3.2
Møgel5	8.2	-21.4	3.2
Møgel6	7.7	-21.2	3.2
Møgel7	7.5	-21.0	3.2
Møgel8	7.1	-20.9	3.2
Møgel9	6.9	-20.7	3.2
Møgel10	7.1	-20.7	3.2
Møgel11	7.5	-20.8	3.2
Møgel13	8.1	-20.9	3.2
Møgel15	8.3	-21.0	3.2
Møgel16	8.3	-21.1	3.2
Møgel17	8.2	-21.0	3.2
Møgel18	8.8	-21.2	3.2
Krej1	9.9	-20.7	3.2
Krej2	9.3	-20.6	3.2
Krej3	9.5	-20.4	3.2
Krej4	9.5	-20.4	3.2
Krej5	9.2	-20.5	3.2
Krej6	9.0	-20.5	3.2
Krej7	9.1	-20.3	3.2
Krej8	9.2	-20.2	3.2
Krej9	9.4	-20.0	3.2
Krej10	9.5	-19.9	3.2
Krej12	10.0	-20.2	3.2
Krej13	10.3	-20.2	3.2
Krej14	10.5	-20.2	3.2
Krej15	10.4	-19.9	3.2
Krej16	10.5	-19.6	3.3
Romb1	11.9	-19.8	3.3
Romb2	11.7	-19.8	3.3
Romb3	11.2	-19.8	3.2
Romb4	10.9	-19.7	3.3
Romb5	10.8	-19.7	3.3
Romb6	10.8	-19.8	3.3
Romb7	11.4	-19.7	3.3
Romb8	11.8	-19.7	3.3
Romb9	12.1	-19.7	3.2
Romb10	12.4	-19.6	3.3
Romb11	12.5	-19.4	3.3
Romb13	12.9	-19.2	3.2
Romb14	13.2	-19.2	3.3
Romb15	13.1	-19.7	3.3
Ryg1	9.6	-20.6	3.3
Ryg2	10.2	-20.5	3.3
Ryg3	10.4	-20.7	3.4
Ryg4	10.3	-20.6	3.4
Ryg5	10.3	-20.4	3.3
Ryg6	10.3	-20.2	3.3
Ryg7	10.1	-20.1	3.3
Ryg8	10.3	-20.0	3.3
Ryg9	10.5	-20.1	3.3
Ryg10	10.9	-20.2	3.3
Ryg11	11.0	-20.1	3.3
Ryg13	11.3	-20.2	3.3
Ryg14	11.4	-20.3	3.4
Ryg16	11.5	-20.3	3.3

Appendix 2. Radiocarbon dates.

Table 3. Conventional and calibrated ^{14}C ages of the human and faunal bone collagen samples used in this study.

Tooth sample number	Location	Bone sample number	Lab no	^{14}C age ± 1σ BP	^{14}C age cal BC/AD (2σ)	Archaeological period	Remarks
Lim-ht-055	Torsholm	Lim-hb-049	UBA-31955	5038 **± 40**	3799-3535 cal BC	Neolithic	This study
Lim-ht-056	Torsholm	Lim-hb-048	UBA-31302	5065 **± 34**	3920-3645 cal BC	Neolithic	This study
Lim-ht-057	Krejbjerg og Ginderup	Lim-hb-044	UBA-31298	4697 **± 34**	3518-3123 cal BC	Early/Middle Neolithic	This study
Lim-ht-058	Krejbjerg og Ginderup	Lim-hb-045	UBA-31299	4142 **± 33**	2866-2574 cal BC	Neolithic	This study
Lim-ht-059	Bjørnsholm (Vitskøl)	Lim-hb-004	UBA-31296	4303 **± 43**	3022-2760 cal BC	Middle Neolithic/ SGK	This study
Lim-ht-060	Nørtorp	Lim-hb-024	UBA-31301	3150 **± 30**	1491-1296 cal BC	Early Bronze Age	This study
Lim-ht-061	Romb	Lim-hb-031	UBA-31300	1259 **± 29**	cal AD 675-867	Germanic/Viking Age	This study
Lim-ht-062	Færkerhede	Lim-hb-005	UBA-31297	3536 ± 54	1944-1662 cal BC	Late Neolithic	This study
Lim-ht-072	Rygegård	Lim-hb-105	UBA-31303	1869 **± 28**	85-232 cal BC	Early Roman Iron Age	This study
Lim-ht-079	Aggersborg Kirke	Lim-hb-001	K-2765			Viking Age	cal AD 1030. Submitted by J. Heinemeier.
Lim-ht-189	Nørhå	Lim-hb-138	UBA-31280	2902 **± 55**	1212-909 cal BC	Early Bronze Age	This study
Lim-ht-190	Lodbjerg klit	Lim-hb-146	UBA-31285	4656 **± 49**	3628-3139 cal BC	Early/Middle Neolithic	This study
Lim-ht-191	Møgelvang	Lim-hb-148	UBA-31286	4180 **± 59**	2901-2586 cal BC	Neolithic	This study
Lim-ht-192	Højvang Mark	Lim-hb-153	UBA-31289	4001 **± 58**	2838-2301 cal BC	Single Neolithic	This study
Lim-ht-193	Næsby Østergård	Lim-hb-182	AAR-10059	3865 ± 60	3772 ± 60	Late Neolithic	Submitted by B. H. Nielsen.
Lim-ht-194	Næsby	Lim-hb-187				Viking Age	
	Hov, flint-mine					Early Neolithic	Other material from Hov dated: Poz-7671, Poz-7675. Submitted by K.A. Soerensen
	Krabbesh-olm II					Early Neolithic	Other material from Krab-besholm II dated: Poz-12163, Poz-12127, Poz-26157, Lus-6138, Lus-6654, Oxa-27066 Submitted by I.B. Enghoff, K.A. Soerensen, L. Sorensen.
	Smedegård					Iron Age	Chicken from Smedegård dated (AAR-3784) 2085 ± 45. Submitted by T. Andreasen.

Circa 2.5-3 mg of collagen was loaded with 0.09 g of copper oxide and a silver strip for contaminant removal in a small quartz tube for combustion to CO_2. Combusted samples were graphitised using a hydrogen reduction method with iron as catalyst. Pressed targets were analysed together with oxalic acid standards and background samples in the NEC compact model 0.5MV AMS at the ^{14}CHRONO Centre in Belfast. Radiocarbon ages were calculated from $F^{14}C$ (Reimer et al., 2004), which is corrected for

background and isotopic fractionation using $^{13}C/^{12}C$ measured by AMS that accounts for both natural and machine isotopic fractionation. An error multiplier of 1.3 was applied to the $F^{14}C$ measurements to account for variability in sample processing. ^{14}C dates were calibrated using Calib 7.0.2 with the mixed marine and Northern Hemisphere terrestrial curves (Reimer et al., 2013) for humans. Based on 13 known age mollusc measurements (Olsson 1980; Heier-Nielsen et al., 1995) from the Limfjord area taken from the marine reservoir database (http://calib.org/marine/), the ΔR and uncertainty were calculated ($\Delta R = 239 \pm 164$ yrs). The percentage of marine carbon was calculated using a linear regression between a fully marine and terrestrial endmember based on $\delta^{13}C$ ratios from marine and terrestrial animals.

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