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Human mobility in the post-Roman Netherlands (AD 400-700)

combined Sr-O isotopic evidence and archaeological contextualization

L.M. Kootker and S. Heeren

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Human mobility in the post-Roman Netherlands: combined Sr-O isotopic evidence and archaeological contextualization
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Contents

Foreword

When I started studying archaeology in 1979 at the former Institute for Pre- and Protohistory in Amsterdam, the study of migratory movements and more generally of human mobility was by no means popular. Within the paradigm of the then dominant processual archaeology, this field of study was considered an exponent of the old cultural-historical archaeology that considered migratory movements as an important explanatory factor for social change in the past. It is only around the last turn of the century that we see a clear shift in the study of human mobility in archaeology; what had previously been almost a taboo subject has now once again become a prominent research topic. This reappraisal cannot be separated from the incorporation of aDNA and isotope data into archaeology; the impact of which some refer to as the Third Science Revolution. Meanwhile, internationally, we are in a phase in which the methods of isotope research are being further refined, and the results evaluated and contextualized through confrontation and integration with archaeological and historical datasets and social theorizing. In this interdisciplinary research, the Late Roman period and the Early Middle Ages are of particular interest. After all, it is precisely for these time periods that we also have high-quality historical and archaeological sources concerning human mobility. These periods are ideally suited to demonstrate the potential of this new field of study.

The present study demonstrates the quality and potential of Dutch archaeology in the field of interdisciplinary isotopic research of human material. Collaborators from the Faculty of Humanities and from the Faculty of Science of the Vrije Universiteit Amsterdam worked closely together and used state-of-the-art science-based methods; while the questioning, contextualization of the data, and final interpretation were based on the latest insights acquired within the field of humanities. Human material from current archaeological Malta practice as well as material collected in the pre-Malta period was used. The presented results provide important new insights. For example, interesting gender-specific patterns are emerging in the mobility of women and men over a longer time span. Here we see the contours of entirely new, quantifiable narratives about which we knew nothing until recently. The study convincingly demonstrates that new insights can only be gained through careful archaeological, historical and social science contextualization. The study is thus not only methodically state-of-the-art science, but also theoretically.

The study convincingly shows the special value and potential of recently developed isotopic techniques, but emphasizes at the same time that this research is no more than an important first step that calls for follow-up research, not only for the period studied here, but also for the other periods. Although the need to integrate isotope studies in archaeology is recognized, further effective integration is needed to produce research of international significance.

The study presented here is the result of a grant by the Cultural Heritage Agency of the Netherlands, but is difficult to realize within the regular Malta practice. Also, within a commercialized practice it is not a given that extra energy is put into both, the scientific technique and the archaeological contextualization and interpretation of the results. Collaboration between a humanity (*alpha*) and a science *(beta)*-oriented scientist should be sought much more often, as should collaboration between governments, universities and implementing companies.

There are clearly opportunities here for Dutch archaeology to further national and international scientific research. In addition, we should not forget that the interdisciplinary isotope research lends itself perfectly to interesting presentations for a broad audience and can therefore contribute to the social profiling of archaeology. After all, it is precisely archaeologically contextualized isotope research that can offer quality narratives about individuals from a distant past.

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Emeritus professor Western-European archaeology
August 2021

Summary

The evidence of migration from the 5th to the 7th century AD can contribute to a broader understanding of relationships, trade, and exchange between regions throughout the North Sea area and with regions further inlands and highlights the important role of human mobility in Early Medieval Europe.

This report presents the combined strontium-oxygen (Sr-O) isotope data of 120 individuals dating to roughly the late 4th to 7th century AD from present-day the Netherlands. The research has been carried out within the framework of the 'Erfgoed Telt' ('Heritage counts') research programme that allowed the Cultural Heritage Agency of the Netherlands (Rijksdienst voor het Cultureel Erfgoed, RCE) to define nine studies to generate new knowledge using modern techniques and a fresh perspective from excavations dating from before the Malta era. This research has provided a first-ever insight into early Medieval palaeomobility patterns in a more quantitative way. These patterns are analysed for six regions within the Netherlands.

A total number of sixteen individuals dated between the very late 4th century and the middle part of the 5th century (circa AD 390 - 470) were included in the isotope analysis. The percentage of individuals that exhibit non-local strontium and/or oxygen isotope compositions is 100%. This high number corresponds to the trends seen in settlement and burial archaeology, which imply a quick re-population after near-complete abandonment or at least displacement of most settlements in nearly all regions in the preceding period. Based on the near equal division of males and females, as well as the presence of non-adults, and a proportion of 94% of the individuals that showed significant isotopic differences between the molars investigated (i.e, intra-individual changes: $\Delta^{87}Sr/^{86}Sr_{Mx\text{-}Mx} \geq 0.0002$) in this period, it can be suggested that communities rather than individuals were involved in this immigration. Whether the re-population happened in a short period of immigration by large groups or was a process of rather small groups immigrating over an extended period of time (decades) cannot be established on the data currently available.

For the late 5th/6th century, 32 individuals were sampled. The percentage of individuals that exhibit non-local strontium and/or oxygen isotope compositions amounts to 53%. The number of individuals that show large (>0.0002) intra-individual changes in $^{87}Sr/^{86}Sr$ is 47% in this period. This is in line with settlement and burial archaeology, suggesting continuity in communities of areas re-populated before, or a new start of communities in areas that were not yet inhabited. Importantly, females dominate the group of individuals of non-local origins. This could fit a model of mobility on a smaller scale, in which exogamy and patrilocal residence were the rule. It implies that communities in newly colonized regions maintained links with communities further afield for both trade and marriage partners and that it was the girls or young women who travelled to the family of prospective husbands.

A total number of 71 individuals dating to the 7th century was included in the current analysis. Corresponding to the trend observed for earlier periods above, the percentage of individuals showing non-local strontium and/or oxygen isotope compositions further decreased to 34%.

The number of individuals that show large intra-individual changes also decreased to 27%. Similar to the 6th century AD, there is an imbalance in the male and female population within the group of non-local individuals; seven males versus 15 female individuals. The picture of less mobility overall and smaller-scale continuation of the suggested exogamy and patrilocal residence is mirrored in the archaeological sources, in which continuity of settlement and burial sites is visible.

The current results are a clear expression of the high potential of this type of research. At the same time, it calls for similar research applied to later periods (8th century and later). Moreover, it would be highly informative to combine the current Sr-O isotopic research with future aDNA analysis of the same individuals, in order to establish familial relations and possibly the regions of origin of the non-local individuals.

Samenvatting

Het aantonen van migratie of mobiliteit in de vijfde tot de zevende eeuw na Christus kan bijdragen tot een ruimer begrip van relaties, handel en uitwisseling tussen regio's in het Noordzeegebied en met regio's verder landinwaarts en benadrukt de belangrijke rol van menselijke mobiliteit in het Europa van de vroege middeleeuwen.

In dit rapport worden de gecombineerde strontium-zuurstof (Sr-O) isotopendata gepresenteerd van 120 individuen die dateren uit ruwweg de late vierde tot zevende eeuw na Chr. uit het huidige Nederland. Het onderzoek is uitgevoerd in het kader van het onderzoeksprogramma 'Erfgoed Telt' dat de Rijksdienst voor het Cultureel Erfgoed (RCE) in staat stelde negen onderzoeken uit te zetten om met moderne technieken en een frisse blik nieuwe kennis te genereren uit opgravingen van vóór het Malta-tijdperk. Dit onderzoek heeft voor het eerst op een meer kwantitatieve manier inzicht verschaft in vroegmiddeleeuwse mobiliteitspatronen. Deze patronen worden geanalyseerd voor zes regio's binnen Nederland.

Een totaal aantal van zestien individuen daterende tussen de zeer late vierde eeuw en het midden van de vijfde eeuw (ca. 390-470 na Chr.) zijn binnen dit onderzoek geanalyseerd. Het percentage individuen dat strontium en/of zuurstofisotopen samenstellingen vertoont die niet vergelijkbaar zijn met het verwachte lokale signaal is 100%. Dit hoge aantal komt overeen met de tendensen in de archeologie van de nederzettingen en de begravingen die wijzen op een snelle herbevolking, nadat de meeste nederzettingen in bijna alle regio's in de voorafgaande periode bijna volledig waren verlaten of op zijn minst waren verplaatst. Op basis van de bijna gelijke verdeling van mannen en vrouwen, evenals de aanwezigheid van niet-volwassenen, en het feit dat maar liefst 94% van deze populatie in deze periode één of minimaal twee keer tijdens de jeugd van locatie is gewisseld ($\Delta^{87}Sr/^{86}Sr_{Mx\text{-}Mx} \geq 0{,}0002$), kan worden gesuggereerd dat vooral gemeenschappen in plaats van individuen betrokken waren bij deze immigratie. Of de herbevolking plaatsvond in een korte periode van immigratie door grote groepen of een proces was van eerder kleine groepen die over een langere periode (decennia) immigreerden, kan op basis van de thans beschikbare gegevens niet worden vastgesteld.

Voor de late vijfde/zesde eeuw zijn 32 individuen bemonsterd. Het percentage individuen met afwijkende ('niet-lokale') $^{87}Sr/^{86}Sr$ en/of $\delta^{18}O_{PDB}$ waarden bedraagt 53%. Het aantal individuen dat grote (>0,0002) intra-individuele veranderingen in $^{87}Sr/^{86}Sr$ vertoont, is 47% in deze periode. Dit is in overeenstemming met de nederzettings- en grafveldarcheologie, waarin veel continuïteit te zien is in gemeenschappen van gebieden die eerder opnieuw bevolkt waren, of op een nieuwe start van gemeenschappen in gebieden die nog niet bewoond waren. Belangrijk is dat vrouwen de groep van individuen van niet-lokale oorsprong domineren. Dit zou kunnen passen in een model van mobiliteit op kleinere schaal, waarin exogamie en patrilokaal verblijf de regel waren. Dit impliceert dat gemeenschappen in pas gekoloniseerde gebieden banden onderhielden met gemeenschappen verder weg, zowel voor handel als voor huwelijkspartners, en dat het de meisjes of jonge vrouwen waren die naar de familie van hun aanstaande echtgenoot reisden.

Een totaal aantal van 71 individuen uit de zevende eeuw werd in de huidige analyse opgenomen. In overeenstemming met de trend die hierboven voor eerdere perioden werd waargenomen, daalde het percentage individuen met niet-lokale $^{87}Sr/^{86}Sr$ en/of $\delta^{18}O_{PDB}$ waarden verder tot 34%. Het aantal individuen dat grote intra-individuele veranderingen vertoont, daalde eveneens tot 27%. Net zoals in de zesde eeuw na Chr. domineren de vrouwelijke individuen de groep van niet-lokale individuen (zeven mannen tegenover 15 vrouwen). Het beeld van minder mobiliteit in het algemeen en mogelijke voortzetting op kleinere schaal van exogamie en patrilokaal verblijf wordt weerspiegeld in de archeologische bronnen, waarin vooral continuïteit van nederzettingen en begraafplaatsen zichtbaar is.

De huidige resultaten zijn een duidelijke weerslag van het grote potentieel van dit type onderzoek. Tegelijkertijd roept het op tot vergelijkbaar onderzoek toegepast op latere perioden (achtste eeuw en later). Bovendien zou het zeer informatief zijn om het huidige Sr-O isotopenonderzoek te combineren met toekomstige aDNA-analyse van dezelfde individuen, om familierelaties vast te stellen en eventueel de regio's van herkomst van de niet-lokale individuen.

Part I

General introduction and framework

1 Introduction

1.1 Human mobility in the post-Roman Netherlands

The transition from the Roman Period to the Early Middle Ages is widely discussed in European historical and archaeological research and also addressed in the Dutch national archaeological research agenda (NOaA).[1] It is a highly dynamic period, not least in demographic terms. The population density of the regions that were (partially) abandoned after the Roman Period increased again, possibly due to the influx of new populations. Greater understanding of this issue is important to better understand the many changes occurring during this period, and regional differences therein. Therefore, this study set out to explore different scenarios that could have led to the post-Roman population increase by applying strontium and oxygen isotope studies to human inhumation remains from the period circa AD 400-700.

1.2 Research framework

In the vision letter 'Cultuur in een open samenleving' followed by the 'Erfgoed telt' policy letter (2018), additional investments in heritage, including archaeology, were announced by the state secretary of Education, Culture and Science (OC&W). The reason for the extra investments were prompted by the identification of several underdeveloped opportunities in the Dutch system of heritage management. As for archaeology, two possibilities mentioned are science-based techniques and an important source of information: old excavations whose material is unpublished and not even fully catalogued or processed, but safely stored in archaeological deposits, the so-called pre-Malta research.

Archaeological research from 2007 onwards is conducted in the framework of legislation implemented as the result of the Netherlands undersigning the Valletta Convention and encompasses fieldwork as well as mandatory publication of the results. Research prior to 2007 is often unpublished. By researching these pre-Malta excavations, the previous investments in fieldwork are now given added value in the form of published results. The current research project is part of the programme 'Kennis voor Archeologie', commissioned by the Cultural Heritage Agency of the Netherlands, and geared towards the two opportunities already mentioned: science-based techniques and pre-Malta research.

In this context, 'science-based techniques' specifically refers to the application of isotope analysis on human skeletal remains. Strontium isotope analysis has been successfully applied to archaeological remains since the 1980s, in the Netherlands since 2008[2], and has proven its potential in palaeomobility studies (Chapter 4). Today, strontium isotope analysis, often in combination with oxygen isotope research, is becoming a staple in the bioarchaeological investigation of ancient human remains in post-Malta research.

1.3 Aims and questions

The period from the Roman era to the Early Middle Ages is characterized by transformation on many levels: state, regional, and local level. As indicated by the traditional name Migration Period (*Völkerverwanderungszeit*), it was once widely believed that large-scale migrations were one of the most notable features of this period.

On the regional and local levels, demographic dynamics are tangible through settlement and burial archaeology. In the southern Netherlands, many Roman-period settlements were abandoned in the 3rd century. Depending on the region, new ones were founded around AD 400, but abandoned again not long after, or the new foundations date to the later 5th century and remained inhabited until the 7th century. Burial data slightly diverges but follows this pattern in main lines. North of the Rhine, the picture is more diverse, ranging from a much later decline and swifter recuperation to decline (or at least archaeological invisibility) over an extended period. For the individual regions, the dramatic drop of population size between the Middle Roman period and the Middle Ages has been recognised for decades; a recent article provides a clear synthesis in which all available regional evidence is combined.[3] Details on the observed demographic decline (based on burials as well as

1 Groenewoudt *et al.* 2017.
2 Kootker 2017.
3 Groenewoudt & Van Lanen 2018.

settlement archaeology) are provided in chapter 6 of this publication.

While the re-population itself is evident, it is much harder to establish what the background is of the growing population. Partial or complete population decline, followed by immigration of foreign groups, could be an explanation. However, that is not the only option. It is also possible that remaining population groups, hardly visible archaeologically, started to increase again, more or less autonomously. A middle way, local demographic growth combined with small-scale immigration, is also possible. If we accept that immigration took place, more questions arise: did the immigration occur in a single phase or period, after which the new communities were locally embedded and functioned independent from their region of origin? Or should a lasting link be envisioned and thus continued small scale mobility between the regions of origin and newly founded communities?

The aim of the current research is to support or disprove the above explanation models for the demographic trends sketched earlier, which can be translated into the following research questions:
1) How many individuals of non-local origin can be detected through the application of combined strontium (Sr) and oxygen (O) isotope analysis of human remains in the burial communities of the 5th to 7th century in the current Netherlands?
2) What is the region of origin of the non-local individuals (if present)?
3) What is the most likely explanation for their presence in communities in the Low Countries, in terms of small- or large-scale migration?
4) How do these results relate to demographic research based on other sources (mainly settlement archaeology)?

1.4 Methods and approach

Through the application of combined Sr-O isotope analysis on human remains buried in the period from the 5th to 7th centuries, a fundamental first insight can be provided into human palaeomobility patterns. However, crucial for a meaningful interpretation of the results is the chronological framework. In this study the burial context was the point of departure. Most were relatively dated by accompanying grave goods, a few were dated by radiocarbon (^{14}C). Previously undated burials were only included if material of well enough quality was available for radiocarbon dating.

The main principle of the strontium isotope technique is to compare the isotopic signatures from an individual, i.e., the strontium that was taken up into the food chain, to the bioavailable strontium of the region where the individual was interred (see Chapter 4). Differences between the $^{87}Sr/^{86}Sr$ of an individual's dental enamel and the local bioavailable strontium range are indicative for mobility. In contrast, similarities between the local bioavailable strontium signature and the individual's $^{87}Sr/^{86}Sr$ indicate residential stability or residential mobility between two geographic locations with similar isotopic signatures. A prerequisite for the interpretation of strontium isotope signatures in archaeological organic materials is the accurate mapping of the spatial variations in bioavailable $^{87}Sr/^{86}Sr$ within the study area.[4] Similar to Sr, knowledge of 'local' oxygen isotope ratios is crucial to infer mobility patterns in ancient populations.

Mapping of bioavailable Sr ratios in the Netherlands is challenging (see Chapter 4). Although a first map is available[5], recent research highlighted the immense complexity of mapping $^{87}Sr/^{86}Sr$ in the Dutch subsurface and underlined the need for a new, more detailed map.[6] Similar to Sr, a first insight into the range of oxygen isotope ratios that could be characteristic of the Netherlands is published.[7] In particular with regards to the Sr isotope system, these maps fail to account for where the main source of Sr for humans, such as grains and other plant foods, originated from. Populations that lived on the banks in the (Holocene) river area possibly farmed on the nearby (Pleistocene) sandy soils. The Sr intake may therefore have been dominated by the $^{87}Sr/^{86}Sr$ of the Pleistocene sandy soils, that undoubtedly would have been higher (i.e., more radiogenic) than that of the Holocene river sediments. In order not to be tempted to make far-reaching statements about mobility that might be falsified in the future, and to overestimate the number of *immigrants*, it was decided not to simply identify (compatible/comparable to) 'local' and 'non-local' individuals and compare

4 Bowen 2010; West *et al.* 2010.
5 Kootker *et al.* 2016.
6 Veselka *et al.* 2021.
7 Kootker *et al.* 2019.

the data to the current 'local' biologically available Sr ratios[8], but to use a well argued, yet relatively wide 'local' range. To contextualise the data, intra-individual mobility, i.e., inter-molar $^{87}Sr/^{86}Sr$ variability within a single individual, will also be considered, by burial community as well as by region and period.

1.5 Structure of this publication

After this introduction, Chapter 2 will position the current research in the framework of migration studies, which have a long pedigree in archaeological study. The study of human mobility is fraught with methodological difficulties, and therefore it is important to state the possibilities and limitations of the current type of research. Subsequently, Chapter 3 will present the source material used here: the excavated burial sites and contexts in their proper geographical and chronological framework. In Chapter 4 the scientific methods used for the actual analytical work will be explained, as well as provide all analytical details. The results are presented in Chapter 5. Finally, Chapter 6 will bring all the research together. The analytical results will be interpreted in the proper regional and chronological framework, in connection to other types of research, mainly settlement research and existing interpretations. Based on this discussion, Chapter 7 will outline the main conclusions more briefly.

1.6 Acknowledgements

In the realization of this report assistance was obtained from various people, to whom we are greatly indebted. First and foremost, this concerns the Cultural Heritage Agency of the Netherlands (RCE) in the person of Bert Groenewoudt, who, as commissioning party, initiated the project and critically monitored the process. Secondly to Menno Dijkstra (University of Amsterdam/Diggel Archeologie) who was willing to review the content of the manuscript.

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8 From Kootker *et al.* 2016.

2 Archaeological framework

2.1 Introduction

In this chapter, the current research will be positioned in the framework of developments within the archaeological discipline. Approaches and theory regarding the archaeology of migration will be sketched, gradually moving from cultural archaeology to scientific approaches.[9] Regarding the question of demographics, the chapter ends with a short section about main trends in population.

2.2 Concise overview of migration approaches in archaeology

There is a deep divide between the Anglophone and German tradition of archaeological research concerning migration. In many German studies particular styles of material culture are associated with ethnic groups and changes in material culture are explained by migrations of peoples. In Anglophone archaeological thought, migrations are approached critically and social change is the preferred explanation for changes observed in the archaeological record.[10]

2.2.1 Culture-historical archaeology

Migration as an academic subject developed in the early 19th century as a result of European colonisation of Africa and the Middle East. Once the monuments of Egypt and other eastern areas were published in Western media, the idea of *Ex oriente lux* was formulated by Western scholars: civilisation spread from Africa to the West.[11] Several archaeologists took this idea further and linked a change in material culture to movements of peoples. The German scholar Gustaf Kossinna formulated the concept of *Kulturkreis* ('culture area'), in which sharply defined archaeological 'provinces' coincide at all times with specific peoples or tribes, usually those mentioned in historical sources.[12] This principle led to *etnische Deutung*, the ethnic interpretation of artefacts based on their form. Spatial distribution maps of specific objects were made, and the distribution of Saxon pottery, for example, was interpreted as the living area of the Saxons.

Mainly, although not exclusively, in German archaeology, cultural-historical studies based on the theory of *etnische Deutung* prevailed throughout the 20th century. For the 3rd to 5th centuries in our study area, the works of Joachim Werner and Horst Böhme were particularly influential.[13] These authors observed a rapid change in material culture, primarily of metal dress accessories, in the later 4th and early 5th century AD in northern Gaul and adjoining areas beyond the Roman frontier. The newly emerging material culture was associated with Franks and Saxons, who took service in the Roman army and later settled in (former) Roman territory, thereby bringing the Frankish and Saxon material culture into northern Gaul.[14] Their studies influenced many others, including Dutch and Belgian researchers.[15] For the later 5th century, various types of brooches were attributed to the Saxons, Thuringians and Burgundians.[16]

2.2.2 Processual archaeology

The longevity of cultural-historical archaeology employing *etnische Deutung* is surprising, especially when seen in comparison with Anglophone archaeology, which largely abandoned this way of thinking in the 1970s. Earlier in the 20th century, Vere Gordon Childe had already used the less specific term 'diffusionism' alongside migration as an explanation for changing material culture.[17] When processual archaeology replaced the cultural-historical paradigm, the focus shifted towards the study of local and regional developments in their landscape setting, and migration virtually ceased being studied from an archaeological perspective. Culture-historical notions of migration were deconstructed and some argued explicitly for a 'retreat from migrationism'.[18]

One of the key arguments against the archaeological approaches is summarized by the maxim 'pots not people': trade could occur over long distances, without people moving along with the goods all the way. Moreover, styles could be copied. In theory, a distribution map could indicate migration or a trade network, but

9 This section is modified after Heeren 2017, 149-153.
10 Cf. Burmeister 2000; Hakenbeck 2008.
11 Hakenbeck 2008, 8-9.
12 Kossinna 1911, 3; cf. Hakenbeck 2008, 10-12.
13 Werner 1958; Böhme 1974.
14 Werner 1958; Böhme 1974, 1999, 2009.
15 For instance Erdrich 1998; Taayke 1999, 2003; Opsteyn 2003.
16 For instance Quast 2009; Martin 2014.
17 Childe 1925.
18 Adams, Gerven & Levy 1978; Burmeister 2000, 539; Hakenbeck 2008, 14-15.

only if the dots represent the find spots of items derived from a single workshop. That, in turn, requires establishing true provenance of finds which was, until recently, nearly impossible to prove by archaeological means.

Another important theoretical objection was that judgements about ethnic groups from the written sources were stereotypes used to 'prove' Roman superiority. Ethnic labels had no bearing on material culture in antiquity.[19] The modern ethnic interpretation of material culture reflects a nationalist identity or origin myth rather than an ancient practice.[20]

2.2.3 Post-processual archaeology

The dismissal of ethnic interpretation led to a general tendency to disregard migration and supra-regional causes for change. Social change and newly emerging identities became the preferred explanation for changes in the archaeological record. Migrations were largely ignored or their occurrence was even denied altogether. As a reaction to these 'localist' or 'immobilist' studies, long-distance movements were once again placed on the agenda, although now the more general term 'mobility' was often used to consider long-distance trade and travel alongside migration.[21]

From the mid-1980s onwards, isotope analysis of human remains offered new hopes of establishing migration by archaeological means (see Section 2.3 and further below). Prehistorians were the first to use the new techniques on human remains of the Bell Beaker Culture, techniques that were applied some years later to those from the Early Middle Ages. While the various methods do indeed offer new potential, the output for the Roman Period is not very influential yet since only small series of isotope samples have been processed and the results allow only limited conclusions.[22]

Another strand of research was proposed by Anthony, Burmeister and Hamerow, who focused attention once again on possible archaeological criteria for recognising migration.[23] By studying the European exploration of North America, Burmeister assessed the extent to which the architectural and artefactual remains represented the original nationality of the settlers. To start with, he established that building style was not a reliable criterion. Scandinavian log cabins were suited to the landscapes that the new settlers encountered, which is why that form was also adopted by migrants of non-Scandinavian origins; many settlers soon abandoned the building traditions of their own region of origin. The same holds true for most subsistence strategies: after the initial failure of the dietary traditions of their homelands, fear of starvation caused new settlers to very quickly adopt the habits of indigenous peoples or earlier successful settlers. The main reason why building style and subsistence strategies developed so rapidly is that these were influenced by the landscape. A second reason was the intensive interaction between various groups of settlers. Burmeister also found practices that did not develop quickly, however. Behaviour or choices that were guided by habit and tradition, such as the interior partitioning of buildings and pottery-making techniques, were termed 'the culture of the private'. Because these 'internal' practices remained relatively stable for a longer period, they are a suitable archaeological criterion for studying migration.[24] The focus on pottery technique (tempering) rather than typology or decoration and on the internal division of buildings rather than their main construction are new directions for archaeologists.

Hamerow studied the influence of northern house-building traditions in Britain in the context of Anglo-Saxon migration. She observed that sunken huts, a common form of outbuilding in the Saxon homelands, were widely adopted and are found dispersed over Anglo-Saxon Britain. At the same time, the three-aisled longhouses that usually dominated the Saxon settlements were not taken up in Britain and are extremely rare. The migrants' choice of another style of main dwelling was apparently influenced by existing architecture and by questions of identity, possibly the wish to look Romano-British.[25] These findings fit nicely with Burmeister's argument: the highly visible main dwellings changed rapidly under the influence of social interaction, while the choice of secondary buildings, linked to daily practices such as weaving and food-processing that took place in the outbuildings, remained unchanged.

An influential study for Roman Period archaeology is the volume *Roman diasporas*, in

19 Brather 2004; Jones 1997.
20 Geary 2002; Halsall 2007; Härke 2004.
21 Chapman & Hamerow 1997; Hakenbeck 2008, 17-18.
22 Examples are Chenery, Eckardt & Müldner 2011; Evans, Stoodle & Chenery 2006.
23 Anthony 1992, 1997; Burmeister 2000; Hamerow 1997, 1999.
24 Burmeister 2000, 2017
25 Hamerow 1997, 1999

which archaeological approaches based on burial ritual and stylistic artefactual study are placed alongside epigraphic studies and isotope analysis.[26] It highlights the need to study Roman period human mobility from different angles. Historians are on the same track, presenting written evidence in combination with studies of neighbouring disciplines.[27]

The most recent development is aimed at a truly interdisciplinary approach in which the various techniques are applied to material from one and the same region or even a single assemblage. Just as isotope analysis and aDNA studies are part of the Third Science Revolution (see Section 2.3), pottery studies have also advanced. Through a combination of WD-XRF, thin-sections and MGR (matrix grouping by re-firing), geological provenance of pottery components can be identified. Additionally, stylistic links of these sherds to previously published regional typologies are sometimes in line with the results of this analysis and sometimes deviating, which is interpreted as indicative for local copying of an artefact style of another region.[28] While one could object that moving pots (and copied pots) still do not prove that people travelled, it is a way of refining distribution maps to show pottery finds with an origin in a certain region and their copies.[29] Moreover, the cited example is based on large amounts of pottery which occurred in close association with other indicators of migration, such as house plans of a deviating type and domesticated animals partly coming from distant areas, probably brought in from other areas on the hoof, and partly of local breed, as can be expected.[30] In this case-study, the various indicators strongly suggest a considerable influx of different Germanic groups, in an area where Roman sources identify the newly occurring Batavians. Therefore, this new avenue of research offers an interesting insight into migration and ethnogenesis.[31]

2.3 Third Science Revolution

The way archaeology is practiced has undergone quite a transformation over the past two decades. According to Kristiansen, the introduction and use of Big Data, the wide application of quantitative methods and modelling, and finally the incorporation of aDNA and isotopic data has led to the 'Third Science Revolution' in archaeology.[32] And while it is evident that the greatest breakthroughs in recent years are due to the unique combination of the above three factors[33], not everyone agrees with the positive tone that the 'Third Science Revolution' usually carries.[34] According to Sørensen this revolution is nothing less than a relegation of archaeology, the human sciences, to a role of subordination to the natural sciences.[35] Ribeiro agrees and convincingly demonstrates that the 'Third Science Revolution' carries the dangers of methodological monism and that archaeology should embody qualitative research instead and embrace a more pluralist attitude to allow for a true multi-disciplinary research into human social behaviour.[36]

Despite several strong (counter) voices, it is evident that since the introduction of isotope research in archaeology, the number of scientific papers has grown from a handful of papers per year in the 1980s to hundreds in the past decade. Also, for Dutch archaeology, the introduction and implementation of isotope research in 2008 has led to a small revolution, perhaps even to a shift in paradigm. The way in which (academic) isotope research is intertwined with (commercial) archaeology in the Netherlands is unique. As are the resulting collaborations and peer-reviewed papers. The aDNA and isotope research has led to a deepening of human osteoarchaeological research and provided new insights into human mobility in Dutch archaeological periods and regions. The large amount of data that has been generated in recent years and will be generated in the coming years, especially now that scientific evidence is provided that isotopic research can be applied to cremated material[37], will benefit the quality and accuracy of synthesis work.

2.4 Possibilities and limitations of burial analysis

Recently, Guy Halsall has argued that the two accepted approaches discussed before, i.e., the retreat from migrationism and the revived theoretical approach of archaeological migration studies, are wrong to base their arguments on the archaeological visibility/invisibility of

26 Eckardt 2010.
27 De Ligt & Tacoma 2016.
28 Habermehl *et al.* in press.; Van Kerckhove *et al.* in prep.
29 Habermehl *et al.* in press.; Van Kerckhove *et al.* in prep.
30 Habermehl *et al.* in press.
31 Habermehl *et al.* in press.
32 Kristiansen *et al.* 2014.
33 E.g., Haak *et al.* 2008; Santana *et al.* 2021.
34 E.g., Larsson 2014; Sørensen 2017.
35 Sørensen 2017.
36 Ribeiro 2019.
37 Snoeck *et al.* 2015; Snoeck, Lee-Thorp & Schulting 2014; Veselka *et al.* 2021.

migration.[38] Halsall's first main point is that archaeologists should accept the fact that migration happened and was indeed an important aspect of daily life, but should not expect to find direct remains of migration in the archaeological record. His second point is that, even if we could identify migrants archaeologically, the identity of the travellers might have nothing to do with their area of origin. Identity is highly flexible and young Germanic men could adopt a Roman military identity in the 4th century as easily as a Late Roman officer could adopt a Frankish identity in the 5th century, for the simple reason that it that would probably advance their careers. It is therefore meaningless to classify objects and practices as Roman or Germanic.[39] Although the point that classical ethnic labels have no bearing on material culture remains valid, Peter Heather disagrees with what he calls the 'Barthian instrumentalist fluidity' of identity.[40] Working on the Visigothic struggle against Rome in the late 4th century AD and their eventual settlement in Aquitaine Gaul in the early 5th century AD, Heather revisits the evidence and argues that group identity is not always as fluid as revisionist studies hold. Although new and different groups joined the Visigoths under that same label applied by the Roman sources (external or etic identity), a part of that group was identical to the Visigoths emerging in the late 4th century and Visigothic self-ascription (emic identity) was a reality.[41]

The key question here, however, is the extent to which such identities can be addressed by (funerary) archaeology. As a last case study, we turn to the detailed study of the Longobards in the 6th century, assumedly moving from Pannonia (current Hungary) to northern Italy.[42] In response to DNA studies departing from modern DNA and relating changes in DNA admixture to population movements of the past, the case study focused on ancient DNA and isotopes extracted from burials in the area, where Early Medieval population movements can be reconstructed fairly detailed through historical sources.[43] Additionally, firm archaeological knowledge is available: nearly all suitable individuals from two large and well-studied cemeteries, Szólád in Hungary and Collegno in Italy, were sampled. Without pre-supposing that individuals or sub-groups within these cemeteries were Longobards, the research group wanted to know whether different genomic groups were present in each cemetery, how these cemeteries were organised, and whether groups or individuals within the cemeteries show close genomic relations. Both cemeteries contain individuals of diverging descent; clearly recognisable are a group of northern/Central European origin and one resembling southern European genome.[44]

Moreover, burial customs and material culture of the graves of southern and northern lineage differ to some extent within the cemeteries. Interestingly, the spread (burial location) within the cemeteries differed: individuals of northern/Central European descent were buried more or less clustered at Szólád and widely spread out at Collegno. Another difference emerged when analysing strontium isotopes. At Szólád, individuals from both ancestry groups display non-local values and probably immigrated into the area. At Collegno, it was mainly the people of northern/ Central European lineage that moved in, while the people of southern European descent ('Italian') seem to be local. Although it might be tempting to interpret the immigrants as Langobards joining the local population, this is far from proven, since this concerns the 6th century only. Still needed is a similar study of 5th century AD cemeteries and baseline studies from both the areas of origin and the new settlement area.[45] Although the link between the historical and archaeological sources is not yet proven, the approach chosen here is very promising indeed.

This case study proves several points, with regard to an archaeological and scientific analysis of burial communities. One should not expect beforehand that historical and archaeological evidence match; the chronological and spatial resolution of historical and archaeological sources differ considerably, and lots of archaeological results over a wide area and spanning several centuries are needed in order to approach such a match. Therefore, in each cemetery, detailed chronology (radiocarbon and artefactual dating) and sampling of whole communities rather than isolated individuals are needed. If any of these factors, i.e., detailed chronologies, isotope analysis, aDNA analysis, or availability of detailed historical sources, is missing, one should refrain from historicising interpretation.

38 Halsall 2012.
39 Halsall 2012, 31-34.
40 Heather 2019.
41 Heather 2019.
42 Geary 2019.
43 Geary 2019, 45-51.
44 Geary 2019, 50-56.
45 Geary 2019, 57-58.

This point should also be applied to the current study. The application of strontium and oxygen isotope analysis on post-Roman human individuals is an important step forward in demographic research of the post-Roman Netherlands, but will not immediately result in a connection to the written sources.

Part II

Archaeological context and analytical methods

3 The archaeological case studies

3.1 Introduction

In this chapter an overview of the archaeological basis for the current study will be provided. Starting out by introducing the geographical setting and chronology, the chapter will then proceed to introduce the archaeological sites and the selection of burials within the sites, as well as the published archaeological dates.

3.2 Landscape, regions, and chronology

The geography of the Netherlands, dominated by lowlands on either side of a river delta, has strongly influenced the life histories of the people inhabiting the area. Large rivers facilitate transport, but on the other hand, inhibit crossing. The landscape, in other words, is directly relevant for human activity, and for migration - the central theme in this research - in particular. This section introduces the archaeologically relevant regions within the Netherlands selected for this research and the chronological framework.

With regards to the natural landscape, two factors are relevant for our research aim. Isotope research as conducted in the current study is dependent on the availability of biological materials from well-preserved burial contexts. Therefore, conservation properties of the soil are important. On a very general level, Holocene parts of the landscape (water, marine and

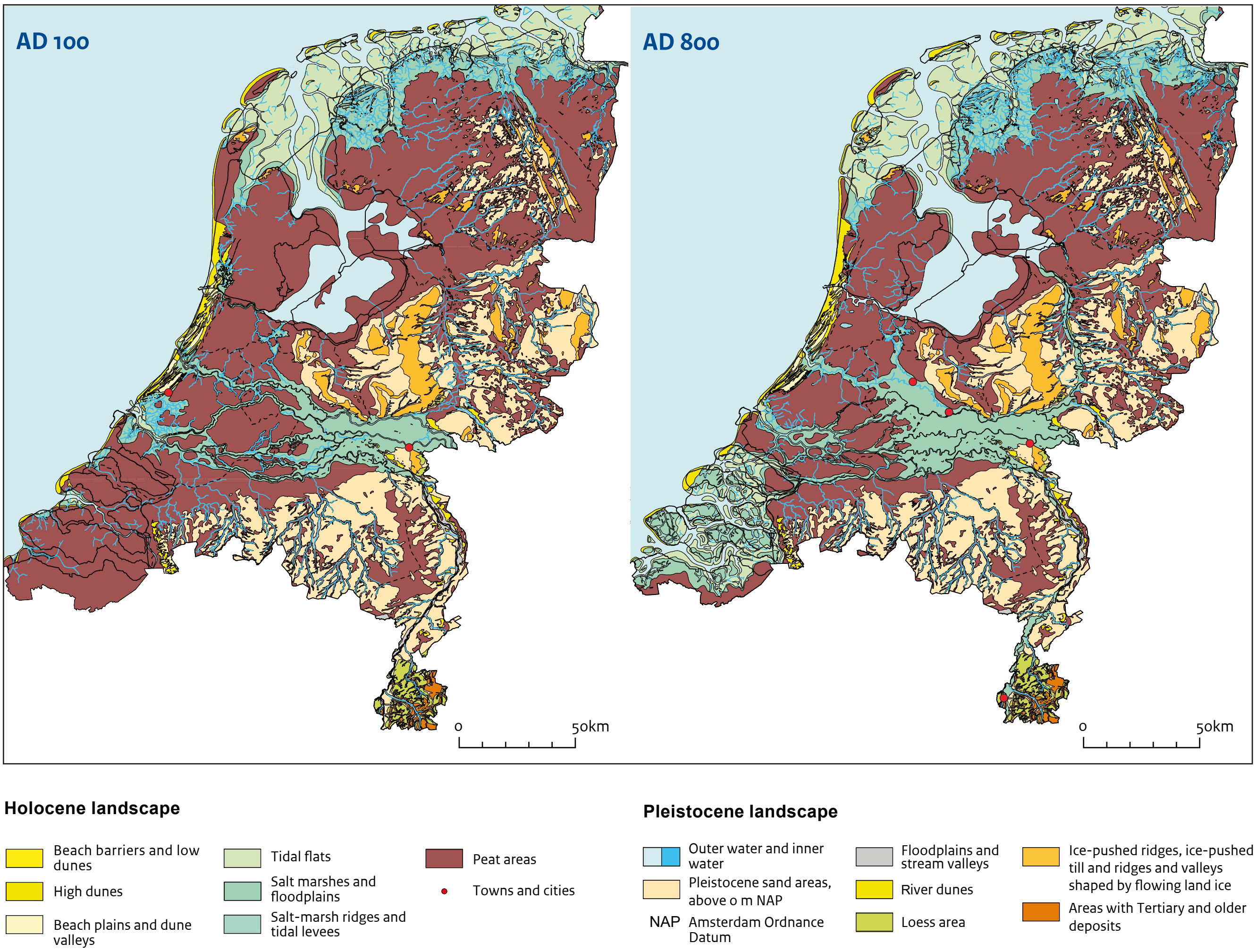

Figure 3.1 Palaeo-geographical map of the Netherlands circa AD 100 and circa AD 800 (Figure by Marjolein Haars (BCL - Archaeological Support) after Vos *et al.* 2020).

Table 3.1 The Dutch 'archeoregio's'.

	Archeoregio (Dutch)	Dominating soil	North/South	Simplified region
1	Drents zandgebied	sand	N	B) northeastern inland area
2	Utrechts Gelders zandgebied	sand	N	B) northeastern inland area
3	Overijssels Gelders zandgebied	sand	N	B) northeastern inland area
4	Brabants zandgebied	sand	S	F) southern inland area
5	Limburgs zandgebied	sand	S	F) southern inland area
6	Limburgs lössgebied	löss	S	F) southern inland area
7	Fries–Gronings kleigebied	clay	N	A) northern coastal area
8	Noord–Hollands kleigebied	clay	N	A) northern coastal area
9	Fries veengebied	peat	N	A) northern coastal area
10	Flevolands kleigebied	clay	N	-
11	Hollands duingebied	dunes (sand)	N / S	C) western delta area
12	Hollands veen– en kleigebied	peat / clay	N / S	C) western delta area
13	Utrechts Gelders rivierengebied	clay	S	D) central and eastern delta area
14	Zeeuws kleigebied	clay	S	E) southwestern coastal area
15	Voordelta / Zeeuwse stromen	water	-	-
16	Continentaal plat	water	-	-
17	Waddenzee / IJsselmeer Markermeer	water	-	-

Source: Cultural Heritage Agency of the Netherlands (RCE)

riverine clay, peat) are favourable for conserving bone and teeth, while the Pleistocene parts of the landscape (sand, gravel, loess, boulder clay) usually result in considerably lower quality of conservation. Enamel is the hardest, densest, and least porous of the mineralised tissues and consequently the most durable of human and faunal tissues. Due to the robust nature of dental enamel, teeth and molars are often preserved in the burial environment, even where all other elements of the skeleton have been completely destroyed by chemical (e.g., soil acidity) or microbial (e.g., fungi, bacteria) attack.[46] However, the absence of all other skeletal remains prevents a thorough osteoarchaeological assessment of the remains. Consequently, the demographic characteristics of the population remain unknown. The interpretation of the isotope data is therefore severely hampered by poor contextual data. Hence, Early Medieval burial sites lacking archaeological context are excluded in this study.

The second factor is topography, and more specifically, the opportunities for travel. As briefly indicated above, rivers do facilitate transport by boat, but in general, they limit crossing by groups of people. The Dutch delta of the rivers Rhine, Waal, and Meuse was a considerable barrier: crossing was not impossible, but would at least have been difficult. Apart from the landscape itself, an additional barrier was formed by the *limes*, the border infrastructure imposed by the Roman authorities on the southern bank of the Rhine. For several centuries, travel across the *limes* was not straightforward. From the 5th century onwards the role of the *limes* limiting cross-river traffic diminished, but the river delta remained. In light of our research aim, a positioning of archaeological sites north or south of the *limes* along the Rhine, or north/south of the river delta, is relevant.

In the past decades, considerable research effort has been invested in studying the Dutch palaeo-landscape. Recent research by Peter Vos, benefitting from that of many others, resulted in palaeo-geographical maps for different periods.[47] Relevant here are the maps for the Roman Period (AD 100 as indicative date; Fig. 3.1a) and the Early Middle Ages (AD 800 as indicative date; Fig.3.1b).

Because of the relation between landscape type and nature, as well as the quality of the

46 See Kendall *et al.* 2018 and references therein.
47 Vos 2015; Vos *et al.* 2020.

archaeological remains, all archaeological research in the Netherlands is related to so-called '*archeoregio's*' (archaeological regions; Fig. 3.2, Table 3.1). Seventeen regions are generally used, covering all parts of the Netherlands and the dominant types of subsoil: Holocene soils, Pleistocene soils, and open water.

For the current research, however, the division in seventeen regions provides too much detail. Since the difference in quality of conservation (soil properties/characteristics) and location south/north of the Rhine is of particular interest, six main regions are defined here:
A) northern coastal area (*Archeoregio's* 7 and 8);
B) northeastern inland area (*Archeoregio's* 1, 2, 3, and 9);
C) the western delta area (*Archeoregio's* 11 and 12);
D) the central and eastern delta area (*Archeoregio* 13);
E) southern coastal area (*Archeoregio* 14);
F) southern inland area (*Archeoregio's* 4, 5, and 6).

Figure 3.2 The Dutch 'archeoregio's'. Source: Cultural Heritage Agency of the Netherlands (RCE). Key: see Table 3.1.

Table 3.2 Burial sites with inhumation burials included in the pre-selection for this study.

Area	Site	Toponym	Reference	Dating (century AD)
A	Hogebeintum	Dorpswierde	Knol 1993; Knol 1995/1996	5th – 8th
	Oosterbeintum	Dorpswierde	Knol 1993; Knol 2019	5th – 8th
B	Elst	't Woud	Verwers & Van Tent 2015	5th – 8th
	Houten	Hoogdijk	Van Dockum 1995	7th – 8th
	Leusden	Oud–Leusden	Van Tent 1988, 19–27.	5th – 8th
	Zutphen	Leesten de Enk	Eeltink 2017	5th
C	Katwijk	Klein Duin	Dijkstra 2011	6th – 8th
	Leiden	Kop van Leeuwenhoek	Goossens, in prep.	6th – 7th
	Oegstgeest	Nieuw Rhijngeest–Zuid	Van Spelde et al. 2021	7th
	Rijnsburg	De Horn	Dijkstra 2011	6th – 7th
D	Bunnik	Het Burgje	-	5th – 6th
	Lent	Azaleastraat	Van Es & Hulst 1991	6th – 7th
	Nijmegen	Hugo de Groot	-	4th – 5th
	Utrecht	Pieterskerk	-	5th
	Wijk bij Duurstede	Veilingterrein	Panhuijsen 2012	7th
	Wijk bij Duurstede	De Geer	Smits & Heeren, in prep.	7th
F	Borgharen	Pasestraat	Lauwerier & De Kort 2014	6th – 7th
	Borgharen	Daalderveld	Van de Graaf & Loonen 2013	5th – 6th
	Born	Buchten	Derks & De Fraiture 2015	5th – 8th
	Gennep	Ven–Zelverheide	Baetsen 1997	5th – 7th
	Maastricht	-	-	6th – 7th

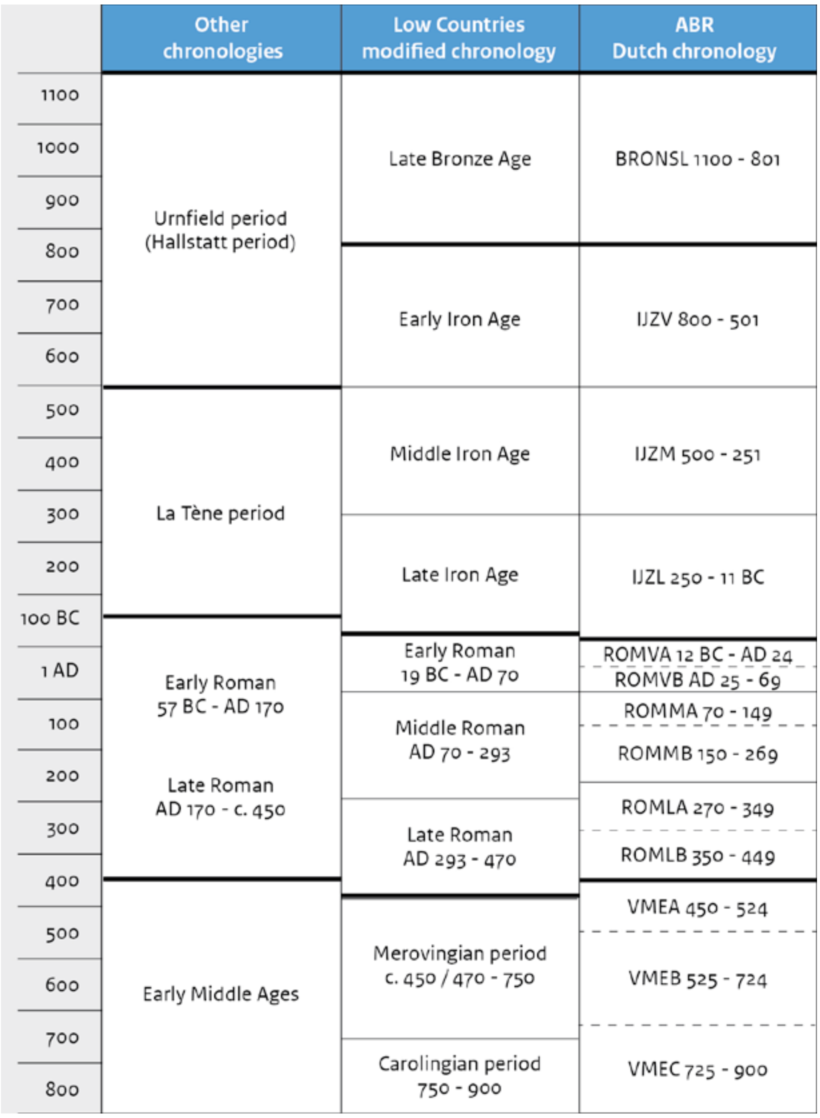

Figure 3.3 Various chronological schemes for the periods covered in this study.

Regarding chronology, this study refers to the system commonly used in Dutch and German archaeology, using a three-period division of the Roman Period (Early, Middle, and Late) and a two-period division of the Early Middle Ages (Merovingian and Carolingian). The relation between this system and other chronologies is shown in Fig. 3.3.

3.3 Archaeological source material: wider pre-selection

As a first step in preparing the current research, a broad pre-selection of burials was made (Table 3.2). Excavation reports or documentation of unpublished projects were accessed in order to evaluate the availability of suitable human remains, in terms of quantity (how many burials were excavated and how many of these still held physical human remains), quality (state of preservation), and context (could the grave be dated, either by artefacts, radiocarbon date, or otherwise).

3.4 The final selection: catalogue of sites and burials

Unfortunately, the literature review itself was insufficient to assess the state of preservation of the human remains. Physical assessments of the excavated materials or consults with excavators were essential to narrow the pre-selection down to the final selection. Not entirely unexpected, not all of the published human remains found in the various archaeological depots were well preserved; only poorly preserved dental crowns, or caps, were available, or, in cases where the skeletal remains were preserved, dental elements were absent. Moreover, it was not possible to pursue an approach both broad and deep. In-depth knowledge about a few communities was preferred over sampling a limited number of individuals from many different sites. Therefore, the majority of the resources was devoted to the available individuals that met our quality criteria (dated burials with well-preserved human remains) from only a few larger sites. Consequently, the final selection differs from the pre-selection.

Table 3.3 shows the dataset that consists of burial evidence with a divergent research history. The first and main group consists of burial evidence excavated in the pre-Malta setting, as was the main focus of the call for proposals. A second much smaller group consists of samples taken from research in the regular Malta practice of contract archaeology. The skeletal remains were analysed and published as usual in the Malta practice; additionally, isotope analysis was done within the framework of the current study. A third group consists of isotope analysis already done in the framework of other studies and the results were added here for comparison. A map depicting the sites is provided in Fig. 3.4.

Table 3.3 Final selection of burial sites and number of Sr-O analyses executed in this study (383 new analyses, 94 previously published datapoints, $N_{total} = 477$).

Area	Site	Toponym	Dating (century AD)	Reference	Number of analysis Strontium	Number of analysis Oxygen
	Pre–Malta excavations					
A	Hogebeintum	Dorpswierde	$5^{th} – 8^{th}$	Knol 1993; Knol et al. 2019	24	24
	Oosterbeintum	Dorpswierde	$5^{th} – 8^{th}$	Knol 1993; Knol et al. 1996	23 in McManus et al. 2013; 16 in this study	16 in McManus et al. 2013; 16 in this study
B	Zutphen	Leesten de Enk	5^{th}	Eeltink 2017	3	3
	Elst	't Woud	$5^{th} – 8^{th}$	Verwers & Van Tent 2015	10	10
	Leusden	Oud–Leusden	$5^{th} – 8^{th}$	Van Tent 1988, 19–27	3	3
C	Rijnsburg	De Horn	$6^{th} – 7^{th}$	Dijkstra 2011, 226–234	19	19
D	Houten	Hoogdijk	$7^{th} – 8^{th}$	Van Dockum 1995	3	3
	Lent	Azaleastraat	$6^{th} – 7^{th}$	Van Es & Hulst 1991	45	45
	Malta–excavations					
A	Harlingen	Midlum	$5^{th} – 6^{th}$	Hielkema 2017	6 in Kootker 2017	6
C	Leiden	Kop van Leeuwenhoek	$6^{th} – 7^{th}$	Goossens, in prep.	4	4
	Oegstgeest	Nieuw Rhijngeest–Zuid – SL Plaza	7^{th}	Van Spelde et al. 2021	3 in Van Spelde & Kootker 2021; 4 in this study	1 in Van Spelde & Kootker 2021; 6 in this study
D	Nijmegen	Hugo de Grootstraat	$4^{th} – 5^{th}$	unpublished	13	12
	Wijk bij Duurstede	Veilingterrein	7^{th}	Panhuijsen 2012	18	17
	Zoelen	Scharenburg	$4^{th} – 5^{th}$	Veldman et al. 2011	3	3
F	Borgharen	Daalderveld	$5^{th} – 6^{th}$	Van de Graaf & Loonen 2013	6 in Panhuijsen et al. 2013; 11 in this study	2 in Panhuijsen et al. 2013; 15 in this study
	Borgharen	Pasestraat	$6^{th} – 7^{th}$	Lauwerier & De Kort 2014	9 in Kootker 2014; 8 in this study	13
	Available Sr–O isotope data					
D	Odijk	Het Burgje	$5^{th} – 6^{th}$	Loopik 2020; Van der Feijst 2020	9 in Kootker, Van der Velde & Heeren in prep.	9 in Kootker, Van der Velde & Heeren in prep.
	Ewijk	Keizershoeve	5^{th}	Blom, Van der Feijst & Veldman 2012	5 in Kootker, Van der Velde & Heeren in prep.	5 in Kootker, Van der Velde & Heeren in prep.
Total					184 new analyses, 61 previouly published	199 new analyses, 33 previously published

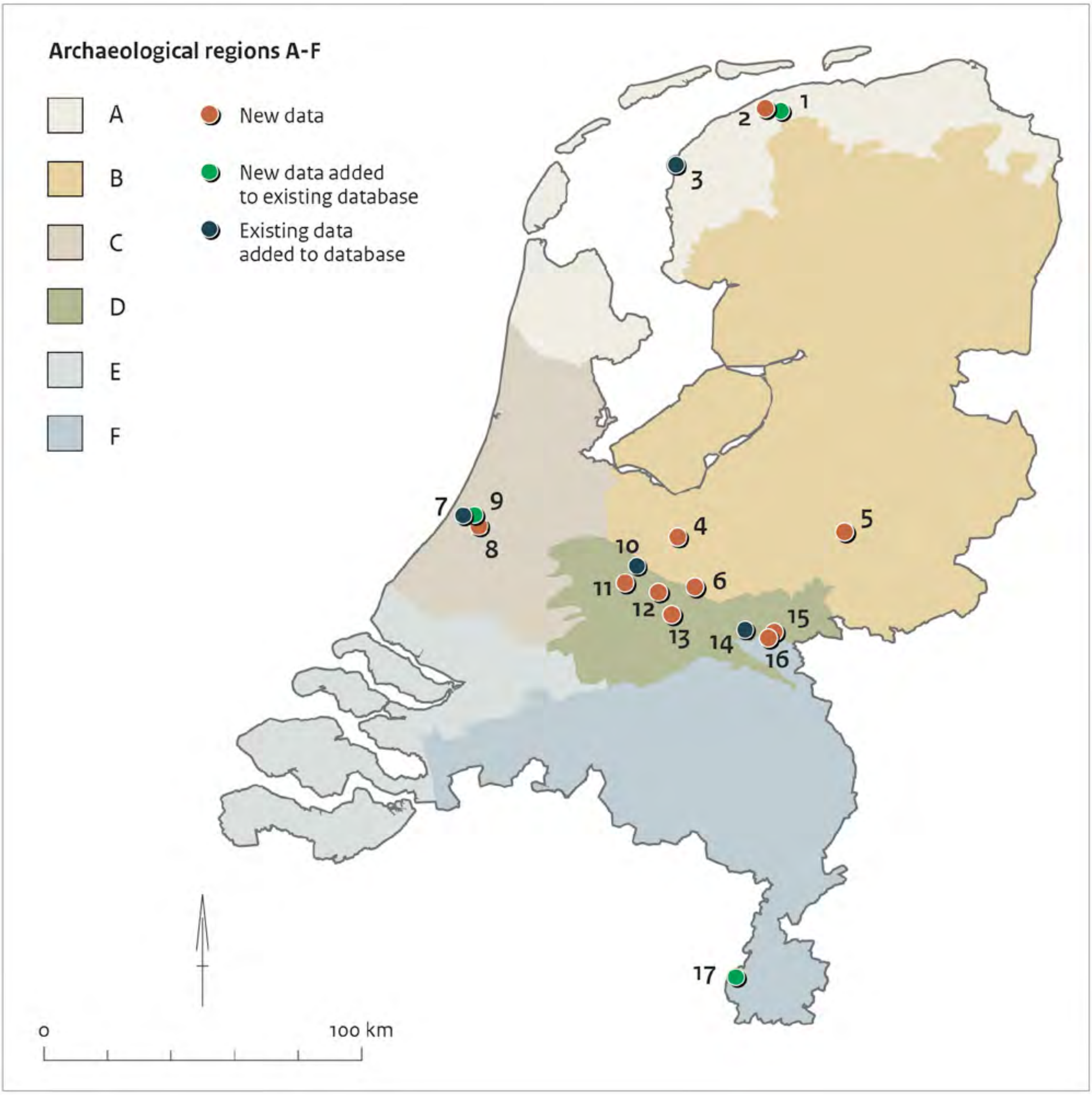

Figure 3.4. Map of the Netherlands with the Early Medieval sites included in this study. Key: 1 – Oosterbeintum; 2 – Hogebeintum; 3 – Harlingen; 4 – Leusden; 5 –Zutphen; 6 – Elst; 7 – Rijnsburg; 8 – Leiden; 9 – Oegstgeest; 10 – Odijk; 11 – Houten; 12 – Wijk bij Duurstede; 13 – Zoelen; 14 – Ewijk; 15 – Lent; 16 – Nijmegen; 17 – Borgharen.

3.4.1 Area A: northern coastal area

The cemetery of Hogebeintum was discovered and researched when the *wierde* was quarried for its fertile soil in 1904-1905. At least 142 burials were documented, but the cemetery must have been (much) larger. Judging from the grave goods and radiocarbon dates of cremated bone and charcoal, the cemetery was in use from the early 5th to the first half of the 8th century (approx. AD 400-730). A few older dates were explained as resulting from the use of old wood for cremation.[48] The catalogue holds at least 94 cremation burials, several buried dogs, and at least 48 human inhumation burials. It also shows whether the material is still held by the depot: some 28 partial skeletons or at least skulls are still kept in the inventory.[49] The skeletal material is still in excellent condition. Ten graves were selected for sampling; a total of 24 dental elements were extracted for analysis. To complement the available ^{14}C dates based on cremated remains, dentine fragments of nine of them were sampled for ^{14}C analysis (FM95, FM96, FM98, FM99, FM100, FM101, FM104, FM107, and FM108). Moreover, five individuals were selected to be included in a Big Data project of the Lundbeck Foundation GeoGenetics Centre at the University of Copenhagen (FM95, FM96, FM98, FM99, and FM101). The biological sex of these individuals has been determined though aDNA analysis and the data are included in the results of this study.

A small cemetery was excavated in 1987 on the southeastern part of the *wierde* of Oosterbeintum. The cemetery held between 33 to possibly 48 cremated burials and 46 inhumation graves. The cremation graves date between the early 5th century and the first half of the 8th century, while the inhumation graves are probably a bit younger, from the second half of the 5th century to the first half of the 8th century.[50] The skeletal material is in good condition. In a previous study, McManus *et al.* already analysed 24 dental elements of the Oosterbeintum population, restricted to a single dental element per individual.[51] In the current research, an additional sixteen samples from eleven individuals were added, overlapping with individuals already done by McManus *et al.*, in order to obtain subsequent molar 1-2-3 data where available. Dentine fragments from ten individuals were sampled for ^{14}C analysis (S60, S335, S360, S410, S435, S460, S483, S486, S487 (485B), and S570). In addition, S487 (485B) was selected for aDNA analysis at the Lundbeck Foundation GeoGenetics Centre at the University of Copenhagen.

Seven inhumation burials were found at Harlingen-Midlum in 2016 during infrastructural works: six females (aDNA data) and one possible male individual. The burials date to the 5th and 6th century (^{14}C data). Six isotope analyses were performed on the six female individuals (I1, I2, I3, I5, I6, and I7). In addition to these data, six C-O isotope values were generated within the framework of this study. The Sr results are published and included here for contextualisation.[52]

3.4.2 Area B: northeastern inland area

At Oud-Leusden a settlement and cemetery dating to the Late Roman Period and Early Middle Ages were unearthed between 1982 and 1984. The provisional report suggests that just two Late Roman burials (5th century) were present, and later graves date from the second half of the 6th into the 8th century.[53] The total number of inhumation burials is around 160. Just a single grave held skeletal material good enough to include in this study. Three molars of an individual of unknown sex (burial 73) were analysed. The archaeological date cannot be specified other than later 6th to early 8th century.

At Zutphen-Leesten a small cremation cemetery dating to the Roman Period was excavated in 1995. One deviating burial was an inhumation grave in a wooden chamber, complete with iron weapons and copper alloy belt components, in style similar to belts current around AD 400.[54] In popular publications, this burial was referred to as 'the Leesten warrior' or 'Gerward', a mythical name. The male individual was between 30 and 50 years old and measured circa 1.55 m.[55] Three molars (M1-M2-M3) from this individual are included in this study.

The cemetery of Elst-'t Woud, excavated and discovered in 1981, is situated just north of the Rhine and comprises 95 inhumations and probably 165 cremation burials, dating from the late 5th century to the early 8th century.[56]

48 Knol 2019, 159-162.
49 Knol 2019.
50 Knol *et al.* 1996.
51 McManus *et al.* 2013.
52 Hielkema *et al.* 2017.
53 Van Tent 1988, 19-26.
54 Groothedde *et al.* 2001, 64-68.
55 Research F. Laarman, cf. Eeltink 2017.
56 Verwers & Tent 2015.

Although the publication shows drawings of burials with bone material present, the preservation conditions are not elaborately described. Unfortunately, the physical assessment of the remains showed that that little bone material was preserved and even fewer of sufficient quality for the aims of the current research. Ten dental elements of five individuals (G174, G178, G210, G238, and G240) are included in this study. All dates and sex determinations were based on grave finds, instead of ^{14}C data and osteoarchaeological analyses respectively.

3.4.3 Area C: western delta area

The first burials of the cemetery Rijnsburg-De Horn were excavated in 1913, while further investigation followed in the late 20th and early 21st century. Although some of the skeletal material of the early research cannot be dated exactly because its contextual connection to the cultural find material is uncertain or lost altogether, it is still useful to analyse these remains since the cemetery was not in use for a very long period. Judging from the finds, the cemetery dates between circa AD 550 to 675/700.[57] The skeletal material is in excellent condition; nevertheless, the number of individuals that could be included in this study was limited. Nineteen samples from nine individuals (1913, E3.2+E4.2, h1913/4.101, Lijk 2.1 - kind, Lijk 2.2 - Volwassene 1, Lijk 2.3 - Volwassene 2, Lijk 5, Lijk 6, and E5) were selected.

Settlement features and two inhumation burials were found at the site of Leiden-Kop van Leeuwenhoek. Radiocarbon dating of these two skeletons was unsuccessful due to the low amount of remaining collagen, but another isolated bone fragment could be dated: 553-648 cal AD.[58] Based on the grave goods, a 7th century seax and a spearhead with a much wider date range, a date in the 6th/7th century can also be assumed for the two inhumation burials (Graf 1 and Graf 2).[59] The remains were of excellent quality. Four molars of the two individuals (two each) were analysed.

In the large Early Medieval settlement of Oegstgeest-Nieuw Rhijngeest, seven primary inhumation burials and several secondary deposits of human remains were identified within a settlement environment.[60] The burials date to the 7th century. Three individuals were available for isotope research (S1, S24, and S8); from each a canine or first molar was already analysed. Four Sr-O analyses from all three individuals were added in the context of this study.

3.4.4 Area D: central and eastern river delta

At Odijk-Het Burgje (or Vinkenburgerweg), municipality of Bunnik, a small cemetery was recently investigated. Within the context of a Middle Roman cremation cemetery, ten inhumation graves were added in the 5th and 6th century. Radiocarbon dates of the skeletal remains failed due to low-quality collagen. However, wood from the burial pits could be dated, resulting in dates between AD 390/400 and AD 600/650.[61] Nine samples from three individuals (INH 5, INH6, and INH7) are analysed. These results have been published and are included here for contextualisation.[62]

The discovery of an isolated inhumation burial of Early Medieval date at the site Houten-Hoogdijk, where Iron Age and Roman settlement remains were expected and found, came as a surprise to the excavators. Based on the grave goods - a spindle whorl, 22 opaque glass beads, a copper alloy pin (sewing needle?), and a copper-alloy decorative openwork disc - the deceased is thought to be female.[63] The openwork disc was stylistically dated to the (first half of the) 7th century.[64] Three molars from the female, identified as 'skelet', were available for combined Sr-O isotope research. A dentine sample was selected for ^{14}C dating.

Settlement remains belonging to an early phase of the later Dorestad settlement were discovered at the excavation of Wijk bij Duurstede-Veilingterrein.[65] Human remains were found between the dwelling features: nine more or less complete inhumation graves and four disturbed features with a single bone or a few bones. The skeletons were found in a prone position, a supine position, or in a crouched position, laying on their side. A total of 18 dental elements from eight individuals (IND1, IND4, IND5, IND6, IND7, IND8, IND90, and IND10) are

57 Dijkstra 2011, 226-227.
58 Brattinga & Goossens in prep.
59 Theuws in prep.
60 Van Spelde & Kootker 2021.
61 Van der Feijst 2020, 30-34.
62 Loopik 2020; Van der Feijst 2020; Kootker 2020; Kootker, Van der Velde & Heeren in prep.
63 Van Dockum 1995, 65.
64 Nieveler & Siegmund 1999, Fig. 1.11, *Rheinland Phase* 8; Theune 1999, Fig. 2.1, *Alamannia Stufe* 4-6.
65 Dijkstra 2012.

included; the other graves are excluded since they do not fit the chronological framework of this study. Three of them (IND 6, IND8, and IND9) were selected for ^{14}C analysis. Four others (IND1, IND4, IND5, and IND7) were dated in previous studies. IND1 and IND7 date to the 7th and 8th century AD (AD 605-673 and AD 600-675 respectively), the other two between the 7th and 9th century AD (IND4 AD 650-780; IND5 AD 640-730: all 2-sigma highest probability).[66] The last individual, IND10, is not dated, but probably belongs to the Merovingian period.[67]

At Zoelen-Scharenburg, a rural settlement consisting of wooden byre-houses, wells, ditches and outbuildings, as well as a cemetery dating from the 1st to 3rd century were investigated in 2007 and 2008.[68] The cemetery primarily consisted of cremation graves, as was customary in that period, and a few inhumations. These inhumation burials date to the 3rd century, contemporaneous with the youngest cremation graves, and one is of a much later date: late 4th/early 5th century.[69] Only the latter (INH3) fits the chronological framework of this project. The Sr-O isotope composition of the other individuals was determined in the framework of a NWO (programme '*Archeologische vondsten van (inter)nationaal belang*') funded project ('*Tiel-Medel: vindplaatsen uit de Romeinse tijd*').[70]

Near the village of Ewijk, on the southern bank of the Waal, the settlement complex De Grote Aalst is situated, known for the remains of a luxurious stone building of the Roman Period. The site produced hundreds of Late Roman coins, among earlier material.[71] Recent developments under the name Ewijk-Keizershoeve prompted new archaeological research in which the settlement surrounding the main building was investigated. In the near proximity of the site two inhumation burials (INH1 and INH2) containing Late Roman military belts and weapons were found, dating to the 5th century.[72] The Sr-O isotope composition of five molars was determined in the framework of a NWO (programme '*Archeologische vondsten van (inter)nationaal belang*') funded project ('*Tiel-Medel: vindplaatsen uit de Romeinse tijd*') and included in this database for comparison.[73]

In the centre of the village of Lent, not far from the northern bank of the river Waal, a Merovingian cemetery was unearthed at Lent-Azaleastraat. Although treated as a single cemetery, in fact there are two clusters: the northern cluster excavated in 1972, of which 26 individuals are excavated, and a southern group in 1975 holding at least 94 burials. The excavators consider these clusters as two burial communities. Judging from the dating of the burial gifts, the northern cluster was dated to the mid-7th century (AD 630-670). The southern cluster contains graves of the same period, but remained in use into the 8th century (AD 750?).[74] Two individuals, (1972/15 and 1972/24) were radiocarbon dated: 575-649 cal AD and 430-602 cal AD respectively In the current research, the Sr-O isotope composition of 19 samples from eight individuals of the northern cluster and 26 samples of 13 individuals of the southern cluster were determined. Dentine samples for ^{14}C analysis of eight individuals (1972/11, 1975/4, 1975/21, 1975/25, 1975/47, 1975/58, 1975/75, and 1975/83) were selected in the framework of this study to further constrain the chronology of this cemetery.

Within the modern borders of the city of Nijmegen, two large cemeteries dating to the Late Roman Period (late 3rd to first half of the 5th century) are known, indicated as cemetery B (inner city) and OO (east).[75] Although the majority of burials was excavated before 1983, modern works touch upon existing remains regularly. When the former Margietpaviljoen was demolished, a new part of cemetery OO could be investigated (Nijmegen-Hugo de Grootstraat HG4).[76] Thirteen dental elements from five individuals (16, 20, 26, 57, and 77) were included in the current study. Three burials (20, 26, and 77) are radiocarbon dated to the 4th century; the other two are assumed to have the same date, although the possibility of a slightly later date (4th - early 5th century) cannot be excluded.

3.4.5 Area F: southern inland area

At Borgharen-Pasestraat, on the bank of the Meuse in Limburg, 24 burials were identified, of which 15 are excavated. The graves date to the Early Middle Ages (second half of the 6th and the 7th century) and were buried in the remains of a Roman villa.[77] Elaborate radiocarbon dating, aDNA research and isotopic analysis were already conducted during that research;

66 Dijkstra 2012.
67 Panhuijsen 2012.
68 Veldman 2011.
69 Veldman 2011.
70 Kootker, Van der Velde & Heeren in prep.
71 Willems 1981, 112, site 239.
72 Van der Feijst & Blom 2012.
73 Kootker, Van der Velde & Heeren in prep.
74 Van Es & Hulst 1991.
75 Steures 2011.
76 Pers.comm. J. Hendriks, gemeente Nijmegen.
77 Lauwerier & Kort 2014; Lauwerier, Muller & Smal 2011.

strontium isotope analysis has been performed on nine dental elements from nine individuals (IND14, IND15, IND17, IND18, IND19, IND20, IND21, IND22, and IND23). An additional eight dental elements from two of those (IND15 and IND18) and four new individuals (GI, GIV, GVII, and GIX) are included in the current research.

Roughly 150 m east of the previous site, an investigation at Borgharen-Daalderveld resulted in the discovery of seven inhumation burials, of which six are included in this study (S1066, S284.1, S372, S747, S822, and S851). Except for S851, all burials are radiocarbon dated. S1066 and S747 date to the 3rd to the early 5th century AD (both 260-430 AD); the others date between the early 5th to the 6th century (S284.1, S372, and S822: all 2-sigma). Based on archaeological evidence, S851 could possibly be dated to a younger period: AD 400-600.[78] Six dental elements from these six individuals were analysed previously (only strontium). In the framework of this study, the Sr-O isotope composition of an additional eleven elements from the same six individuals was determined.

[78] Panhuijsen *et al.* 2013; Van de Graaf & Loonen 2013.

4 Scientific methods

4.1 Introduction

There are several isotope systems that can be used in the study of palaeomobility, such as carbon (C), sulphur (S), oxygen (O), neodymium (Nd), lead (Pb), and strontium (Sr). The application of isotope geochemistry has proven its added value in archaeology, as evidenced by the many scientific publications released in recent years – from Ötzi in Italy to King Richard III in the United Kingdom – all studies share one common denominator: strontium isotopes.[79] The strontium isotope system is considered a relatively straight-forward isotope system and, most importantly, one of the most effective for identifying human and faunal mobility and pinpointing possible (geo)locations of origin. Nevertheless, the power of research into ancient mobility lies in the combination of evidence: archaeological finds and contexts, historical data (if present), and (baseline) isotope data all contribute to a better understanding of the archaeological site and ultimately the development and history of the Netherlands and its inhabitants. The same applies to isotope research itself: the power of this methodology to determine possible regions or origin lies in the combination of isotope systems (e.g., Sr-O-C-N).

For this project, a combined Sr-O approach was chosen to gain valuable information into post-Roman human mobility in the Netherlands. When generating the oxygen isotope data, carbon isotope data are also generated. This system provides insight into the diet, which, to this day, varies somewhat by region.[80] For example, the diet in the southern and eastern parts of Europe used to contain much more millet, a so-called C_4 plant, resulting in a significant different $\delta^{13}C$ compared to a 'typical' diet of an inhabitant of North-western Europe. While the $\delta^{13}C$ data are reported in Appendix II of this report, the isotope system itself and the results of the analyses are not discussed in this and the following Chapter.

4.2 General background

4.2.1 Strontium isotopes

Strontium, an alkaline earth metal, has four naturally occurring stable isotopes: ^{84}Sr (0.56%), ^{86}Sr (9.87%), ^{87}Sr (7.04%) and ^{88}Sr (82.53%). ^{87}Sr is a radiogenic isotope, derived from the radioactive decay of ^{87}Rb ($t_{1/2}$ of $4.88 \cdot 10^{10}$ years).[81] However, because mineralised tissue accepts virtually no rubidium, there is no radioactive source able to change the amount of ^{87}Sr in for instance bone and dental enamel. Consequently, the strontium isotopic signature can be considered stable in mineralised tissue. The ratio (radiogenic) ^{87}Sr to (stable) ^{86}Sr (conventionally expressed as the $^{87}Sr/^{86}Sr$) serves as a geochemical signature that can be used as a powerful proxy to identify non-locally born or raised human individuals and animals in archaeological contexts[82], to aid forensic identification processes[83], or to authenticate the geographical origins of food products.[84]

Spatial variations in the initial amount of ^{87}Rb in and the lithologic composition of the geological bedrock and the age of the geologic substrate have resulted in the geographical distribution of ^{87}Sr.[85] The strontium isotopic signature of geological materials is taken up in our food chain through eroding geological bedrock, soils, vegetation, and livestock. Fractionation of $^{87}Sr/^{86}Sr$ is negligible because of the large atomic mass of strontium and the fact that ^{87}Sr is only 1.16% heavier than ^{86}Sr. This means that Sr isotopes pass from bedrock to soil into biologically-available solutions retaining the same ratio of ^{87}Sr to ^{86}Sr.[86] Moreover, any possible fractionation in $^{87}Sr/^{86}Sr$ would be corrected for upon mass spectrometry by a routine normalisation to the constant $^{88}Sr/^{86}Sr$ (of 8.37521).[87] Non-geological sources of strontium, such as strontium derived from rainfall, dryfall (dust), sea-spray, and modern fertilizers also contribute to the biosphere and are taken up by the food chain.[88] Both geological and non-geological sources contribute to the biologically available strontium; i.e., all strontium present in the biochemical environment. It is this so-called bioavailable strontium signal that gives us insight into migration patterns and palaeomobility (Fig.

79 Kutschera & Müller 2003; Lamb *et al.* 2014.
80 Calvin & Benson 1948; Koch, Hoppe & Webb 1998; Van der Merwe 1982.
81 Steiger & Jäger 1977.
82 Bentley 2006; Brusgaard, Fokkens & Kootker 2019; Groot, Evans & Albarella 2020.
83 Bartelink *et al.* 2014; Degryse *et al.* 2012; Kootker *et al.* 2020.
84 Drivelos & Georgiou 2012; Vinciguerra *et al.* 2016; Voerkelius *et al.* 2010.
85 Beard & Johnson 2000; Capo, Stewart & Chadwick 1998; Faure & Mensing 2005.
86 see Bentley 2006 and references therein.
87 Beard & Johnson 2000.
88 Bentley 2006; Maurer *et al.* 2012.

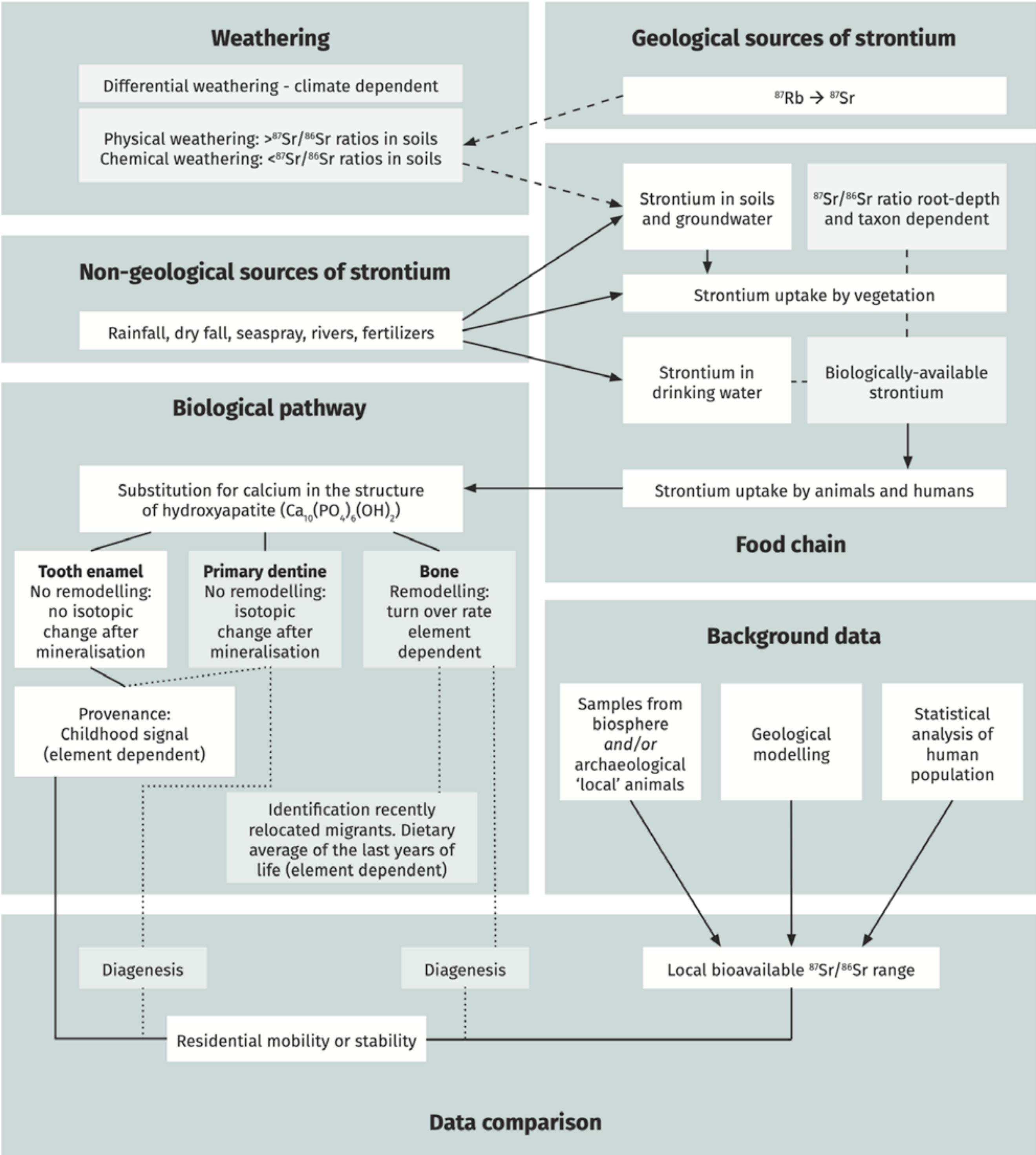

Figure 4.1. Schematic diagram showing the basic principle of strontium isotope analysis of archaeological skeletal material. Key: - - - - $^{87}Sr/^{86}Sr$ dependent on differential weathering or differential uptake; ····· biomaterials susceptible to diagenetic alterations. Modified from Tütken, Knipper & Alt 2008 and reprinted from Kootker 2017.

4.1).

Strontium is incorporated in dental enamel through our diet, where it substitutes for calcium in the structure of bioapatite ($Ca_{10}(PO_4)_6(OH)_2$), a calcium phosphate mineral. While bone is constantly remodelled during life, tooth enamel is not. Dental enamel is formed during childhood and undergoes almost no change after mineralisation due to the loss of the enamel forming cells (ameloblasts) after eruption.[89] Different dental elements can be seen as time capsules to different periods in life; the mineralisation and maturation age of dental enamel varies between dental elements, and between ethnicities, ranging from the peri-natal period (first molars, M1) to approximately 16 years of age (third molars, M3) in permanent dentition.[90] Although ameloblasts are lost after eruption, enamel remineralisation may take place at locations where enamel demineralisation has taken place[91], such as the abrasive (i.e., the occlusal, distal, and mesial sides) and carious surfaces. A recent study on modern human dental enamel from Dutch individuals showed that carious elements exhibited larger intra-individual differences in isotope composition than seen in unaffected elements. The latter, however, also showed variations greater than 0.000200 in $^{87}Sr/^{86}Sr$.[92]

In contrast to dental enamel, bone and dentin are organic rich (20% compared to max. 2% in enamel), poorly crystalline, and very porous.[93] As a result, bone and dentine in particular are very susceptible to post-mortem alterations and are subject to complex diagenetic processes. Diagenesis of strontium in skeletal tissues is a very important consideration in archaeological isotope studies and has been thoroughly studied.[94] More importantly, experimental studies have focused on the distinction between biogenic and diagenetic strontium, but none of them have yielded satisfactory results. Even after pre-treatment with successive rinses in weak acids, the bones still retained a significant amount of diagenetic strontium.[95] As a result, the $^{87}Sr/^{86}Sr$ of an ancient bone or dentin fragment will not represent the biogenic strontium ratio present at the time of death, but rather the (diagenetic) $^{87}Sr/^{86}Sr$ of the burial environment.

Unlike bone and dentine, the large constituent phosphate crystals in enamel[96] and its compact structure make it more resistant to diagenetic alterations. Nevertheless, enamel is also susceptible to the uptake of diagenetic strontium.[97] Diagenetic strontium can be found at the outer surface of the cusp, as well as towards the enamel-primary dentine border; both locations are therefore avoided during sampling.

In her paper 'Passports from the past', Janet Montgomery highlights the two limitations of the strontium isotope system: being an exclusive technique it can only rule out places of origin, and a strontium isotope ratio is rarely unique.[98] So once *immigrants* are identified, the next inevitable question "where did they come from?" is rarely easy to answer, if it can be answered at all. First, in order to identify immigrants, strontium isotopes in (fossil) tooth enamel must be compared to the local bioavailable strontium, which can be potentially delineated by measuring archaeological teeth of assumed local mammalian species. This approach has proven to be a very sensitive and reliable indicator of approximating the Sr isotope baseline ratios.[99] However, it does not take trade or exchange of livestock nor the consumption of imported edible vegetation into consideration; activities that have taken place throughout Europe from the Neolithic period onwards.[100]

Today, various other methodologies have been proposed to delineate the local strontium baseline values, and ultimately to construct the (local) isotopic landscape (often coined as *isoscape*), such as 1) the use of (archaeological) small rodent species and/or (small) mammals that forage in a restricted area; 2) biosphere samples (vegetation: trees, shrubs, and grasses); and 3) soil samples.[101] Every proxy chosen to represent the bioavailable strontium ratio has its advantages and disadvantages. An in-depth, but regionally applicable study by Maurer *et al.* emphasized the difficulties in determining the sources of strontium that enter the local food chain.[102] Moreover, they confirmed the offset in $^{87}Sr/^{86}Sr$ between geological, biosphere and faunal samples.[103] Consequently, the most careful and reliable approach to define the local bioavailable strontium range may therefore be found in the combination of the aforementioned methodologies. Today, bioavailable strontium isotope maps are available for several countries, such as the Netherlands (Fig. 4.2), the United Kingdom, Ireland, Denmark, Italy, and France.[104]

89 Jussila, Juuri & Thesleff 2013.
90 Nelson & Ash 2010; Reid & Dean 2006; Woelfel & Scheid 2002.
91 Franklin & Hicks 2008; Selwitz, Ismail & Pitts 2007.
92 Plomp *et al.* 2020.
93 LeGeros 1981.
94 Budd *et al.* 2000; Copeland *et al.* 2010; Kendall *et al.* 2018; Kohn, Schoninger & Barker 1999; Nelson *et al.* 1986.
95 E.g., Hoppe, Koch & Furutani 2003.
96 Hand 2014.
97 Lewis 2015.
98 Montgomery 2010.
99 Bentley 2006; Bentley & Knipper 2005; Bentley, Price & Stephan 2004; Price, Burton & Bentley 2002.
100 Bakels & Jacomet 2003; Bentley & Knipper 2005; Grumbkow *et al.* 2013; Livarda 2011; Madgwick, Mulville & Evans 2012; Oelze, Nehlich & Richards 2012; Van der Jagt *et al.* 2012.
101 See Holt, Evans & Madgwick 2021 for an extensive overview and critical review of the different proxies used in archaeology.
102 Maurer *et al.* 2012.
103 Price, Burton & Bentley 2002; Price *et al.* 2003.
104 Bataille *et al.* 2018; Emery *et al.* 2018; Evans *et al.* 2016; Evans, Montgomery & Wildman 2009; Evans *et al.* 2010; Frei & Price 2012; Kootker *et al.* 2016; Snoeck *et al.* 2020; Willmes *et al.* 2018.

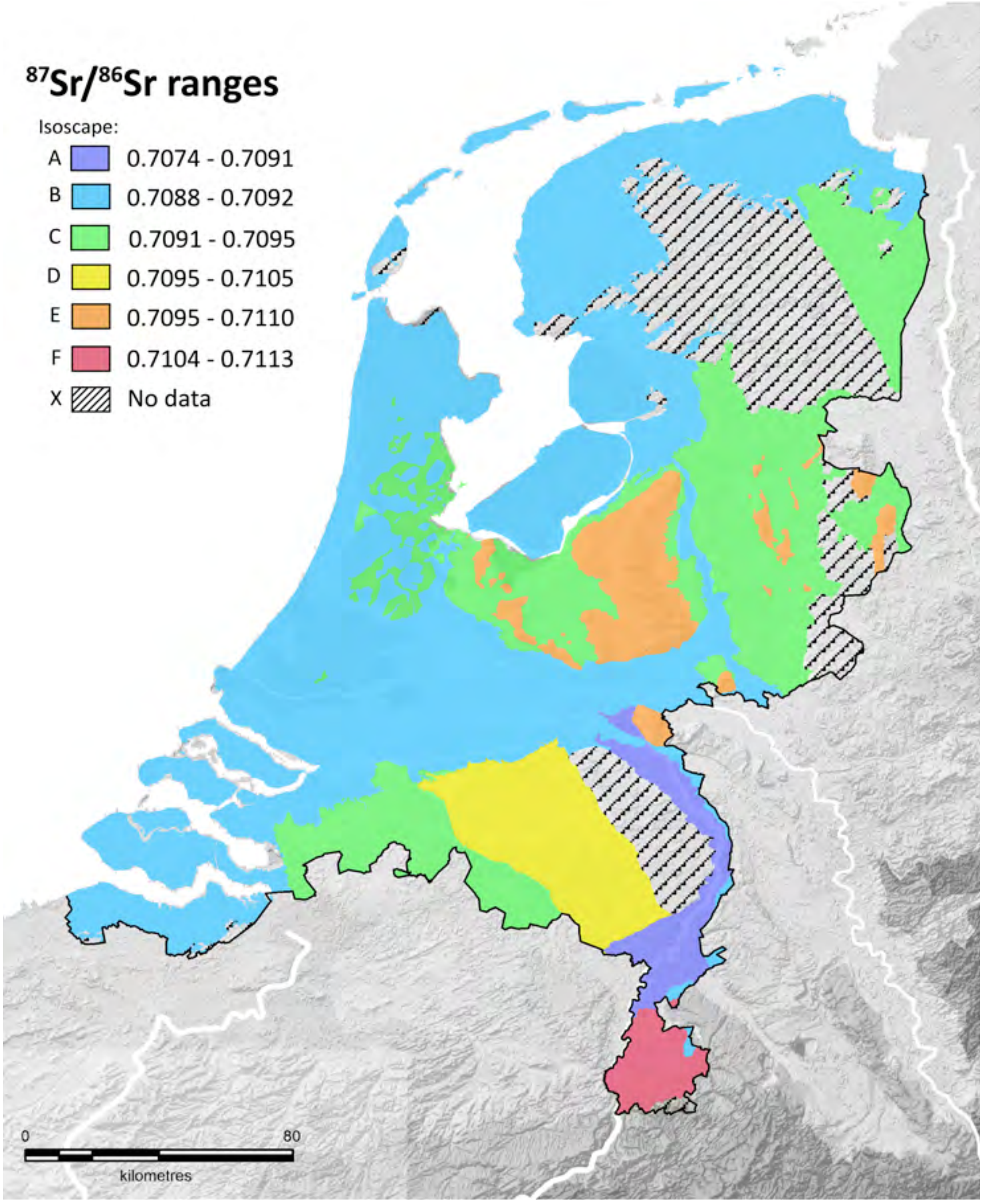

Figure 4.2. Bioavailable strontium isoscape of the Netherlands. Reprinted from Kootker *et al.* 2016, with permission from Elsevier (license number 5104661418594).

4.2.2 Oxygen isotopes

In contrast to strontium isotopes, oxygen isotopes offer a different type of isotopic discrimination, independent of the underlying geology. Oxygen has three stable isotopes: ^{16}O (99.76%), ^{17}O (0.04%), and ^{18}O (0.20%).[105] Because the isotopic differences between the stable oxygen isotopes are rather small, the data are reported as delta values in per mil notation (‰) relative to a standard of known composition.[106]

$$\delta\ (‰) = (R_{sample} / R_{standard(scale\ zero\ point)}) - 1$$

Where R is the ratio of the heavy to the light isotope. The isotopic composition of oxygen is conventionally expressed as the ratio $^{18}O/^{16}O$ (or $\delta^{18}O$) relative to Vienna Standard Mean Ocean Water (VSMOW) for water samples[107] or Vienna PeeDee Belemnite (VPDB or PDB) for carbonate

105 Faure & Mensing 2005.
106 McKinney *et al.* 1950; Schoeller 1999; Werner & Brand 2001.
107 absolute ratio VSMOW, $R_{standard}$, for $^{18}O/^{16}O$ = 0.0020052: Baertschi 1976.
108 absolute ratio VPDB, $R_{standard}$, for $^{18}O/^{16}O$ = 0.0020672: Mook 2001.

samples.[108]

Isotopes of oxygen primarily vary with climate (temperature) and precipitation gradients (through the principle of Rayleigh distillation), but subtle effects are introduced by latitude, altitude and water source. In general, the $\delta^{18}O$ decreases with: 1) distance from the sea, 2) increase in altitude, 3) increase in latitude, and 4) decrease in temperature (Fig. 4.3).[109] In Europe, this translates into a west-east gradient of precipitation from the North Atlantic and a less extreme south-north gradient from the Mediterranean. The geographic variation in the isotopic composition of precipitation is extensively mapped at both regional and global scales. These maps can be used as a proxy for human and animal palaeomobility, since the spatial variation of the $\delta^{18}O$ of precipitation seem to be directly related to the spatial variation of environmental water resources such as groundwater and lakes, and drinking water, although local modifications due to evaporation loss do occur.[110] However, the delineation of local $\delta^{18}O$ values might be more complex and challenging than previously thought. Large intra- and inter-archaeological site variations in human $\delta^{18}O$ values have been recognised, as have high degrees of overlap in human oxygen isotope values in Europe.[111]

Oxygen isotopes are incorporated in the carbonate hydroxyapatite crystals of tooth enamel and bone tissue through ingestion of drinking water, absorbed water in food, and through inhalation.[112] Similar to strontium isotopes studies, tooth enamel has become the preferred material because of its resistance to diagenetic alterations and hence its better preservation of the biogenic isotope signal. Currently, oxygen isotope composition of apatite is analysed using different techniques. Some target the oxygen derived from the structural carbonate group (CO_3), a more rapid and costs effective approach, while others measure the phosphate oxygen (PO_4). It has been thought that that oxygen isotopes in carbonates ($\delta^{18}O_C$ or $\delta^{18}O_{PDB}$) are more prone to diagenetic alteration than oxygen isotopes in phosphates ($\delta^{18}O_P$), due to the energetically more stable P-O bond.[113] More recent research by Chenery and colleagues, however, demonstrated that *analysis of the structural carbonate ion for $\delta^{18}O_C$ values is both accurate and precise*.[114]

The $\delta^{18}O_P$ and $\delta^{18}O_{PDB}$ are strongly correlated with $\delta^{18}O_{DW}$ (mean annual precipitation values). This allows the calculation of the ingested

[109] see Schwarcz, White & Longstaffe 2010 and references therein.
[110] e.g., Bowen *et al.* 2007; Dutton *et al.* 2005; Kennedy, Bowen & Ehleringer 2011; Smith *et al.* 2002.
[111] Lightfoot & O'Connell 2016.
[112] Schwarcz, White & Longstaffe 2010.
[113] Kohn & Cerling 2002.
[114] Chenery *et al.* 2012.

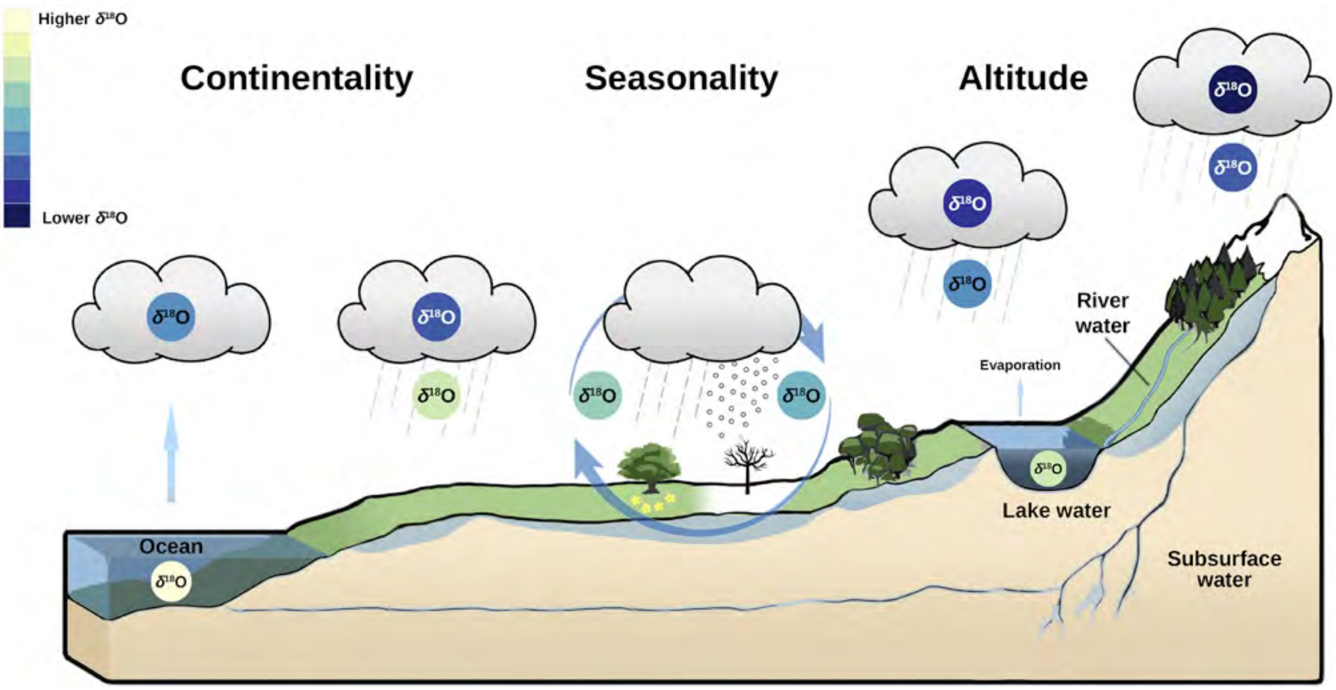

Figure 4.3. Isotopic baseline variation in $\delta^{18}O$ is introduced in the hydrological cycle as water $\delta^{18}O$ is changed by rainout and evaporation processes, that results in large scale effects of continentality, seasonality and altitude, as well as temperature, rainfall amount, and relative humidity. Reprinted from Pederzani & Britton 2019, with permission from Elsevier (license number 5104661217969).

Table 4.1. Published equations to recalculate $\delta^{18}O_{PDB}$ data to $\delta^{18}O_{VSMOW}$, $\delta^{18}O_{P}$, and $\delta^{18}O_{DW}$

Equation	Reference
$\delta^{18}O_{VSMOW}$(‰) = (1.0309 * $\delta^{18}O_{PDB}$) + 30.91"	Coplen 1988.
Cold, temperate and warm humid climates:	
$\delta^{18}O_{P}$(‰) = (1.0322 * $\delta^{18}O_{VSMOW}$) - 9.6849	Chenery *et al.* 2012.
Hot-arid climates:	
$\delta^{18}O_{P}$(‰) = (1.122 * $\delta^{18}O_{VSMOW}$) - 13.73	Iacumin *et al.* 1996; Metcalfe, Longstaffe & White 2009.
$\delta^{18}O_{DW}$(‰) = (1.590 * $\delta^{18}O_{VSMOW}$) - 48.634	Chenery *et al.* 2012.
$\delta^{18}O_{DW}$(‰) = (1.54 * $\delta^{18}O_{P}$) - 33.7	Daux *et al.* 2008.

$\delta^{18}O_{DW}$, which can be seen as characteristic of the area of residence or the area of birth. Direct relationships between $\delta^{18}O_{PDB}$ and $\delta^{18}O_{DW}$ have not yet been established. The conversion from $\delta^{18}O_{PDB}$ to drinking water values therefore requires a number of steps, which are species specific. Firstly, the $\delta^{18}O_{PDB}$ values need to be converted into the VSMOW scale, where after the $\delta^{18}O_{DW}$ can be calculated. For human bioapatite samples, the equations presented in Table 1 are established.

The use of these conversion equations, however, undoubtedly introduces errors. Previous research show that the error associated with conversion equations can be as high as 1 ‰ to circa 3.5 ‰.[115] Although these studies refer to the regressions of phosphate oxygen versus drinking water, the same principles also apply to the carbonate oxygen. The obtained converted data therefore will be used as a guide rather than accepted as accurate values.[116]

To date, the interpretation of oxygen isotope data is challenging. The definition of a local oxygen isotope baseline is a complex procedure. Large intra- and inter-site variations in human $\delta^{18}O$ values across Europe have been recognised. Recent studies show the existence of a high degree of overlap in (archaeological) human oxygen isotope values in Europe and advocate not using oxygen isotope analysis alone for provenancing purposes.[117] Therefore, an integrated approach has been adopted to achieve the best possible resolution in the delineation of local oxygen isotope signals.

Ideally, to avoid the uncertainties associated with the available conversion equations (see above), human and (faunal) background $\delta^{18}O_{PDB}$ or $\delta^{18}O_{p}$ data are used to enable direct comparisons between the investigated population and the local regions against which the generated data can be compared.[118] However, the development of (regional/national) datasets containing local (human and faunal) $\delta^{18}O_{PDB}$ data is still in its infancy.[119] Hence, one has to rely on the existing (modern) drinking water values to detect a relation between measured oxygen isotope values and geographic regions.[120] For this reason, the obtained human $\delta^{18}O_{PDB}$ values are converted to $\delta^{18}O_{DW}$ values to allow such a comparison between the obtained human and the environmental data. In this study, 'local' $\delta^{18}O_{DW}$ data from 1) the Global Network of Isotopes in Precipitation[121], 2) modern tap water samples from the Netherlands[122], 3) the schematic West-European $\delta^{18}O_{DW}$ isoscape map[123], 4) $\delta^{18}O_{PDB}$ data of modern individuals from the Netherlands who had not spent more than 30 days outside the Netherlands between the age of 7 and 16[124], and 5) a statistical assessment of the archaeological Oldenzaal $\delta^{18}O_{PDB}$ data[125] were combined to define the local oxygen isotope signal.

4.3 Analytical details of the current study

4.3.1 Radiocarbon (^{14}C) dating

To achieve a high success rate and to obtain reliable ^{14}C measurements, root dentine was sampled from each selected individual (n = 28, see Chapter 3). Dentine is occasionally better preserved than bone, because the roots of the teeth are protected from external influences by the lower or upper jaw. The sample consisted of one cut-off root, using an acid-cleaned Dremel

115 Chenery *et al.* 2012; Pollard, Pellegrini & Lee-Thorp 2011.
116 cf. Chenery *et al.* 2012, 315.
117 e.g., Lightfoot & O'Connell 2016; Pellegrini *et al.* 2016.
118 Lightfoot & O'Connell 2016; Pellegrini *et al.* 2016; Pollard, Pellegrini & Lee-Thorp 2011.
119 see Pellegrini *et al.* 2016 for a first geostatistical model of spatial variation in the distribution of unconverted human $\delta^{18}O_{phosphate}$ data.
120 Chenery *et al.* 2012. NB Although water sources can be mixed in the Netherlands (see Kootker *et al.* 2020), isotopic differences between source locations are small to nil due to the small geographical distance between sources (Kootker *et al.* in prep).
121 GNIP: IAEA/WMO 2016.
122 Font *et al.* 2015a, 2015b.
123 Compiled by C. Chenery, based on Darling, Bath & Talbot 2003; Lecolle 1985.
124 Font *et al.* 2015a, 2015b.
125 Kootker *et al.* 2019.

Figure 4.4. Overview of the standard workflow for strontium isotope analysis. Key: 1 – sampling dental enamel; 2 – dissolving the samples in HNO_3 in a clean laboratory; 3 – strontium extraction/separation by column chromatography; 4 – loading 1 µl of sample on a rhenium filament; 5 – Finnigan MAT 262 TIMS equipment at the Vrije Universiteit Amsterdam; 6 – data collection (photos Lisette M. Kootker).

circle cutter at low speed to avoid thermally induced cellular damage. The samples were stored in zip-lock bags and sent to the Tandem Laboratory AMS facility at Uppsala University in Sweden with all documentation, where the sample preparation and measurements (^{14}C, $\delta^{13}C$, and $\delta^{15}N$) were carried out.

4.3.2 Sample preparation for Sr-O isotope analysis

The dental elements were selected at various archaeological depots and museums and transported to the Vrije Universiteit Amsterdam for further treatment (Fig. 4.2). If possible, the dental elements were identified using the FDI (Fédération Dentaire Internationale) two-digit notation system (ISO3950, Appendix I). If a tooth could not be designated a number, for instance a first or second molar, it was identified as 'M' (molar) or 'M1/2'.

Every element was mechanically cleaned to expose a dull white surface visually unaffected by diagenetic alterations using an acid-leached diamond-tipped drill bit. Approximately 10 milligrams of enamel powder were sampled from the mesial or distal lobe of either the buccal or lingual surface, depending on the physical quality of the molar and the presence of carious lesions, and collected in 2 ml screw cap glass vials.

4.3.3 Strontium isotope analysis

Between 1 and 3 mg enamel powder was subsampled, sealed in 6-7M HCl-cleaned polyethylene Eppendorf centrifuge tubes, and transported to the class 100 clean laboratory at the Vrije Universiteit Amsterdam. The samples were leached with 0.1M acetic acid (CH_3CO_2H) to remove labile diagenetic strontium[126], and eventually dissolved in 3.0M nitric acid (HNO_3). Strontium was isolated by ion exchange chromatography using Sr-Resin (ElChroM©) and collected in acid-leached Teflon® vials (Savillex). Blanks were spiked with ^{84}Sr. All samples were nitrated twice with concentrated HNO_3 and dried down.

[126] Hoppe, Koch & Furutani 2003.

Next, the samples were dissolved in 2 µl 10% HNO_3, and 1 µl was loaded on single annealed rhenium filaments using 2 µl $TaCl_5$. The measurements were performed using a Thermal Ionization Mass Spectrometer (TIMS: Thermo Scientific TRITON Plus) at the Vrije Universiteit Amsterdam using a static routine. The isotope ratios were corrected for mass-fractionation to $^{86}Sr/^{88}Sr$ = 0.1194. The NBS987 standard gave a mean $^{87}Sr/^{86}Sr$ of 0.710279 ± 0.000009 (n = 59). The current certified $^{87}Sr/^{86}Sr$ of NBS987 is 0.71034 ± 0.00026 (certificate issue date 19 June 2007); however, the quoted accepted ratios vary significantly (between circa 0.710240 to 0.710263).[127] In this study, the measurements were all normalised to an accepted $^{87}Sr/^{86}Sr$ of 0.710240. For every sample batch the correction factor was calculated (0.710240/$^{87}Sr/^{86}Sr_{measured\ NBS}$) and applied to the sample batch. The procedural blanks contained between 18.0 and 66.2 pg strontium (n = 25); a negligible amount compared to the concentration of Sr in human dental enamel (50-500+ ppm, thus at least 50 ng (50,000 pg) in a 1 mg sample).

[127] E.g., Irrgeher, Galler & Prohaska 2016; Linderholm *et al.* 2020.

4.3.4 Oxygen isotope analysis

Circa 0.3 ± 10% mg enamel powder was weighed into a glass Exetainer® vials with screw-capped pierceable butyl rubber septa and transferred to the Stable Isotope Laboratory at the Vrije Universiteit Amsterdam. The prepared vials were placed in a sample block interspaced with calibration and control standards VICS and IAEA-603. After flushing the vials with helium, samples and standards were acidified with water-free H_3PO_4 (100%) at 45°C and allowed to react for 24 hours. The gas mixture was analysed using a Thermo Finnigan Delta plus IRMS with a GasBench II. The isotopic values are reported as δ-values in ‰ units (see eq. 1). Values were normalised to international standard IAEA-603 ($\delta^{18}O$ = −2.47 ± 0.17 ‰ and $\delta^{13}C$ = 2.47 ± 0.13 ‰ (1σ, n = 40)) and are reported relative to the Vienna Peedee Belemnite (PDB) standard.

Part III

Data

5 Results and interpretation

5.1 Introduction

In this chapter, all published and newly generated Sr-O isotope data and ^{14}C dates are presented and briefly discussed. A complete overview of all ^{14}C dates and Sr-O-C isotope data is provided in Appendix II.

5.1 Dating

The dating of the burials selected for the current research (Chapter 3) are generally based on two dating tools. The first is the traditional typochronological dating of artefacts. The second is radiocarbon dating (elaborated upon in Chapter 4). In the majority of burials these methods arrived at more or less the same archaeological date. In a small number of cases, the ^{14}C results are reason to critically evaluate the artefactual date.

5.1.1 Typochronological dating

Generally speaking, the date of excavated burials is often established by a typochronological date of the grave goods associated with the skeletal remains. For the current research, we based the selection of burials on published catalogues (Chapter 3). The typochronological dates are therefore, in general, taken over from existing work. In one case, that of Houten-Hoogdijk, no date was published and therefore the artefact date of the 7th century is our own.

5.1.2 Radiocarbon (^{14}C) dating

The results of the radiocarbon analyses executed at the Tandem Laboratory AMS facility at Uppsala University in Sweden are presented in Table 5.1. All data used in this study are reported with 2-sigma error.

Graves FM96, FM99 and FM101 from Hogebeintum resulted in dates between the mid 3rd century and the (very) early 5th century. Although a date in the very early years of the 5th century is still possible, especially burial FM99 would be a reason to include the final years of the 4th century in the dating of the cemetery.

The graves from Oosterbeintum all date to the 5th/6th to 6th/7th century AD. In most of the cases, the obtained ^{14}C dates confirmed the catalogue dates that were based on typochronological analysis of the burial gifts, or stratigraphy (relative date established by one grave intersecting an older grave). In the case of S435 however, the relative date established on the basis of two such intersections (circa AD 550-700)[128] was probably incorrect, since the radiocarbon date was established at 431-577 cal AD.

Based upon the grave goods, the isolated inhumation burial at the site Houten-Hoogdijk, was expected to date to the 7th century. [129] The ^{14}C dating, however, suggested the earlier part of that range (599-658 cal AD).

Based on the relative dating of the burial gifts, the northern cluster of graves at Lent Azaleastraat was dated to the mid-7th century (AD 630-670), while the southern cluster was expected to remain in use into the 8th century (AD 750?).[130] Based on additional radiocarbon dates, this chronology should be adapted. Burials 1972/11 and 1972/24[131] from the northern cluster are at least a full generation earlier than previously thought and probably date to the 5th or 6th centuries, or the very early 7th. Individuals 1975/04 and 1975/47[132] from the southern cluster are also older than previously thought and date to the later 6th or early 7th century.

5.2 Sr-O isotope analysis

Depending on the number of data points, the combined Sr-O data are presented either per site or per (part of an) '*Archeoregio*'. The data are presented in tables and visualised in graphs. In order to present the data as accurately as possible, it was decided not the visualise the local $^{87}Sr/^{86}Sr$ signatures. The current Sr isoscape of the Netherlands is based on archaeological rodents and a few wild mammalian species.[133] Although this is a generally accepted approach, the diet of these animals differs significantly from that of humans. This may not lead to complications in regions with homogeneous soil

128 Knol *et al.* 1996, 401.
129 Nieveler & Siegmund 1999; Theune 1999.
130 Van Es & Hulst 1991.
131 Courtesy J. Hendriks, additional dates of Azaleastraat in the framework of the Lent-Lentseveld cemetery.
132 Courtesy J. Hendriks, additional dates of Azaleastraat in the framework of the Lent-Lentseveld cemetery.
133 Kootker *et al.* 2016.

Table 5.1. ^{14}C data (2-sigma error) from 28 individuals from Hogebeintum and Oosterbeintum (Area A), and Houten and Lent (Area D). Radiocarbon ages are calibrated using IOSACal (v0.4.1) and atmospheric data from Reimer *et al.* (2020).

Site	Lab ID	Sample	^{14}C date (BP)	Calibrated date	$\delta^{13}C$ ‰ (PDB)	$\delta^{15}N$ ‰ (AIR)	C:N
Hogebeintum	Ua–69911	FM 96	1688 ± 28	AD 258 – AD 419	−19.8	11.2	3.2
	Ua–69913	FM 99	1684 ± 28	AD 258 – AD 422	−20.3	11.2	3.2
	Ua–69915	FM 101	1677 ± 29	AD 257 – AD 432	−19.8	10.4	3.2
	Ua–69917	FM 107	1614 ± 28	AD 414 – AD 539	−20.6	11.2	3.2
	Ua–69916	FM 104	1588 ± 28	AD 420 – AD 546	−19.7	12.9	3.2
	Ua–69910	FM 95	1587 ± 29	AD 419 – AD 547	−19.9	10.9	3.2
	Ua–69918	FM 108	1570 ± 28	AD 426 – AD 562	−19.8	11.0	3.2
	Ua–69914	FM 100	1484 ± 28	AD 551 – AD 640	−19.6	9.5	3.2
	Ua–69912	FM 98	1287 ± 28	AD 662 – AD 774	−19.7	10.4	3.2
Oosterbeintum	Ua–69995	S60	1611 ± 27	AD 416 – AD 538	−19.8	13.7	3.2
	Ua–69997	S360	1575 ± 28	AD 424 – AD 557	−19.8	12.2	3.2
	Ua–70002	S486	1571 ± 28	AD 426 – AD 561	−20.1	11.0	3.2
	Ua–70000	S460	1569 ± 28	AD 427 – AD 563	−20.6	9.9	3.2
	Ua–70003	S487 (485B)	1561 ± 27	AD 430 – AD 569	−20.3	11.7	3.2
	Ua–70004	S570	1561 ± 27	AD 430 – AD 569	−20.2	9.1	3.2
	Ua–69998	S410	1556 ± 28	AD 430 – AD 575	−19.4	9.1	3.2
	Ua–69999	S435	1554 ± 28	AD 431 – AD 577	−19.3	7.7	3.2
	Ua–69996	S335	1535 ± 28	AD 435 – AD 599	−19.5	11.6	3.2
	Ua–70001	S483	1477 ± 27	AD 558 – AD 643	−20.6	9.9	3.2
Houten	Ua–69927	Skelet M1	1417 ± 27	AD 599 – AD 658	−19.6	12.4	3.2
Lent	Ua–69987	1972/11	1506 ± 27	AD 537 – AD 610	−20.3	13.0	3.2
	Ua–69991	1975/47	1497 ± 28	AD 542 – AD 640	−20.2	13.8	3.2
	Ua–69988	1975/04	1466 ± 28	AD 565 – AD 646	−20.4	10.4	3.2
	Ua–69990	1975/25	1337 ± 28	AD 649 – AD 772	−20.3	11.0	3.2
	Ua–69992	1975/58	1335 ± 28	AD 649 – AD 772	−20.2	11.2	3.3
	Ua–69994	1975/83	1251 ± 28	AD 674 – AD 876	−20.4	11.9	3.2
	Ua–69989	1975/21	1250 ± 28	AD 674 – AD 876	−20.4	11.5	3.2
	Ua–69993	1975/75	1232 ± 28	AD 684 – AD 882	−20.1	11.0	3.2

profiles, but it does in regions with heterogeneous soil profiles; i.e., where a thin layer of marine clay is deposited over a thick layer of Pleistocene sediments. Consequently, to date, the local or regional $^{87}Sr/^{86}Sr$ signatures (i.e., the $^{87}Sr/^{86}Sr$ that are incorporated into the *human* diet) in for instance the northern coastal area (area A in this study) and the southern inland area (area F) are not yet well defined and subject to change.[134] Therefore, to avoid data overinterpretation and overestimation of the number of non-local individuals (immigrants), it was decided to adopt a more cautious approach in presenting the findings.

A similar approach was applied to the $\delta^{18}O_{PDB}$ data. Based on the available reference datasets (see Section 4.1.2), a relative wide range of 'local' $\delta^{18}O_{PDB}$ values was defined. In this study, all $\delta^{18}O_{PDB}$ values between −6.5 and −4.0 ‰ are considered to be comparable to or compatible with the 'Dutch' signature. These values translate to a 'local' $\delta^{18}O_{DW}$ range between −10.1 and −6.0 ‰. All values exceeding these ranges are indicative of a non-local origin

In this study, a multiple dental-elemental approach was applied to obtain as much information as possible on intra-individual mobility patterns. Based on a study with

[134] But see Veselka *et al.* 2021 for a more detailed biosphere Sr map of Limburg.

Table 5.2. Combined Sr-O data from Hogebeintum (n = 24, all executed within the framework of this study). $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.12 (average 0.08). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; * – biological sex based on aDNA.

Sample ID	Sex	^{14}C code	From	To	Element	$^{87}Sr/^{86}Sr$	$\delta^{18}O_{PDB}$	$\delta^{18}O_{DW}$
FM95 – kist 249	M*	Ua–69910	419	547	36	0.710382	−4.77	−7.31
					37	0.710669	−6.15	−9.57
					28	0.709513	−5.79	−8.97
FM96 – kist 249	M*	Ua–69911	258	419	26	0.710270	−5.27	−8.13
					17	0.710618	−5.57	−8.61
					38	0.709540	−5.60	−8.66
FM98 – kist 249 II	M*	Ua–69912	662	774	46	0.709288	−5.39	−8.32
					47	0.709129	−5.31	−8.19
					48	0.708928	−5.80	−8.98
FM99 – kist 249 II	M*	Ua–69913	332	403	46	0.710224	−6.53	−10.18
					47	0.710896	−6.32	−9.85
FM100 – kist 249 II	–	Ua–69914	551	640	36	0.713396	−4.28	−6.49
					37	0.713417	−4.02	−6.08
FM101 – 28–360	F*	Ua–69915	257	432	46	0.711104	−4.78	−7.33
					37	0.711370	−5.82	−9.02
					48	0.710635	−5.45	−8.41
W98 – FM104 – kist 250 II	–	Ua–69916	420	546	16	0.709162	−4.74	−7.26
					17	0.709129	−5.69	−8.81
FM107 – kist 251	F	Ua–69917	414	539	26	0.710485	−6.20	−9.64
FM108 – kist 251	–	Ua–69918	426	562	46	0.709848	−6.06	−9.42
					37	0.710019	−6.04	−9.39
FM109 – kist 251	–	–	–	–	36	0.709115	−3.70	−5.56
					47	0.709126	−4.11	−6.23
					48	0.709091	−4.36	−6.63

modern human individuals from the Netherlands, intra-individual variations of up to 0.0002 can occur within the crown of a single element.[135] Consequently, in this study, although focused on archaeological populations, a minimum variation of 0.0002 ($\Delta^{87}Sr/^{86}Sr_{Mx-Mx}$) was used to demonstrate intra-individual mobility.

5.2.1 Area A: northern coastal area

The human combined Sr-O data from Area A, containing the sites of Hogebeintum, Oosterbeintum, and Harlingen, are presented in Tables 5.2-5.4 and, except for Harlingen, depicted in Figs 5.1 and 5.2.

The ten selected individuals from Hogebeintum date from different periods. The burial field was in use from the 3rd/4th century until at least the late 6th/7th century. One individual, FM109, has not been dated, nor is it listed as an inhumation in the catalogue.

Given its close proximity to the coast, and the relative homogeneity of the local/regional shallow subsurface geology, the strontium isotope data display a surprising degree of heterogeneity. The Sr data range between 0.708928 (male, FM98, AD 662-774) and 0.713417 (unknown sex, FM100, AD 551-640), the $\delta^{18}O_{PDB}$ values between −6.53 ‰ (male, FM99, AD 332-403) and −3.70 ‰ (FM109). If the majority of the dietary Sr of the Hogebeintum population originates from the nearby environment, and the vegetation therefore

[135] Plomp *et al.* 2020.

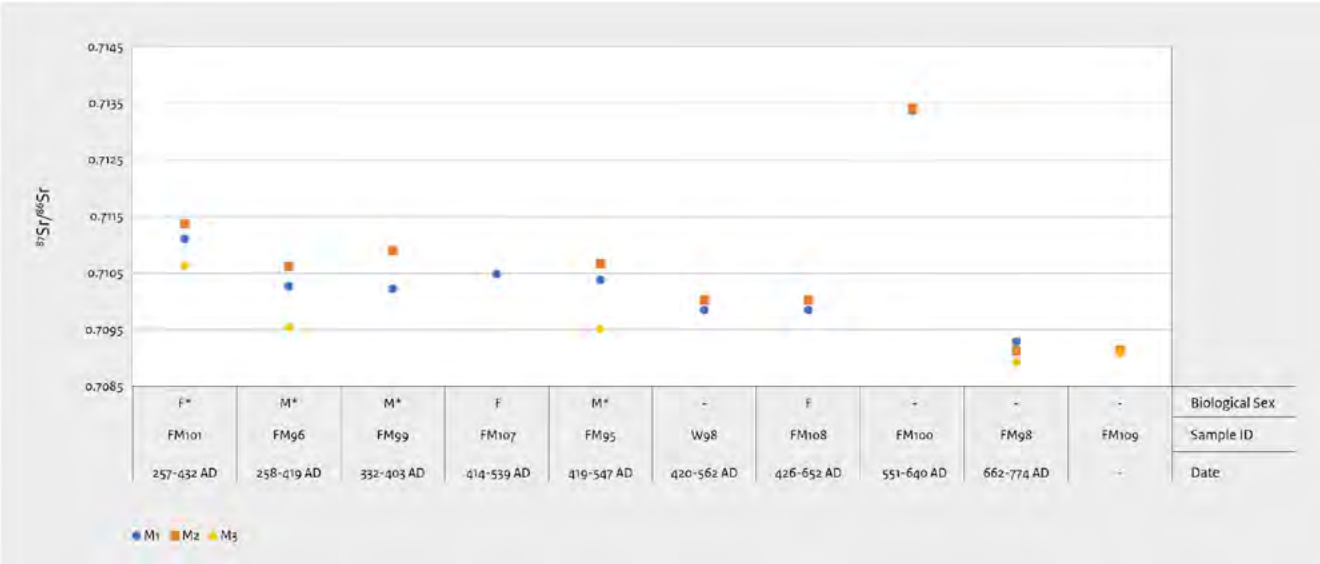

Figure 5.1. $^{87}Sr/^{86}Sr$ data from Hogebeintum. Key: M1 – first molar; M2 – second molar; M3 – third molar; F – female; M – male; - – sex undetermined; * – biological sex based on aDNA; ** – ^{14}C dates.

rooted in the Holocene (sea) clays, then the "local" Sr signature could vary from approximately 0.7088 to 0.7095. Taken both this and the $\delta^{18}O_{PDB}$ range into account, as much as 80% (8/10) of the selected individuals is not from the Hogebeintum region.

In individuals FM101, FM96 and FM95 a significant shift in $^{87}Sr/^{86}Sr$ can be observed between the second and third molar (M2 and M3; Fig. 5.1), indicating mobility after the age of 8, but before the age of circa 16. The $^{87}Sr/^{86}Sr$ of the third molars of FM96 and FM95 are compatible or comparable with the expected regional signature; in FM101, however, the M3 still exhibits a more radiogenic ratio. The Sr ratios of FM109 do not provide evidence for mobility, but the $\delta^{18}O_{PDB}$ is relatively high (–3.70 ‰) and may exclude an origin in present-day the Netherlands.

The selected individuals from Oosterbeintum date between the 5th/early 6th century AD until the 7th/8th century. The dating of the Oosterbeintum cemetery therefore partly overlaps with that of Hogebeintum. Two samples were shared with the University of Copenhagen for aDNA research. In two cases, new information was revealed. Burial S487 (485B), of undetermined sex in the catalogue,[136] is proven to be female. Burial S570, sexed as female? in the catalogue,[137] is now confirmed as female.

Due to its close proximity to Hogebeintum, circa 1 km as the crow flies, a similar regional $^{87}Sr/^{86}Sr$ signature for Oosterbeintum can be defined (0.7088-0.7095). The Sr data range between 0.708156 (male, S335, AD 435-599) and 0.716448 (male, S460, AD 427-563), the $\delta^{18}O_{PDB}$ values between –7.61 ‰ (male, S460, AD 427-563) and –4.00 ‰ (male, S410, AD 430-575). In nine individuals, no Sr-O evidence is provided for mobility. Consequently, mobility is evident in 14 individuals (61% of the selected population). In all except one individual (F335) the $^{87}Sr/^{86}Sr$ are higher, i.e., more radiogenic, than the expected regional signature, indicating dietary Sr originating from older (Pleistocene) sediments. In S335, a 6th-century male, the isotopic shift between the second and third molar is remarkable (0.7092 to 0.7081). In addition, the $\delta^{13}C_{PDB}$ of the first molar (36) deviates significantly and exhibits a positive value, possibly indicating a diet richer in millet (–9.93 ‰; average total population –13.06 ‰). The highest $^{87}Sr/^{86}Sr$ are seen in S460, a 5th/6th-century male. Here, both Sr-O indicate a non-local origin; the associated oxygen isotope ratio even precludes origins in present-day the Netherlands.

From Fig. 5.2 it is evident that (intra-individual) mobility occurs throughout all periods, but the greatest variation in intra- and inter-individual $^{87}Sr/^{86}Sr$ occurs in the first periods that the burial field was in use; approximately between early 5th/mid 6th century

136 Knol *et al.* 1996, 405.
137 Knol *et al.* 1996, 408.

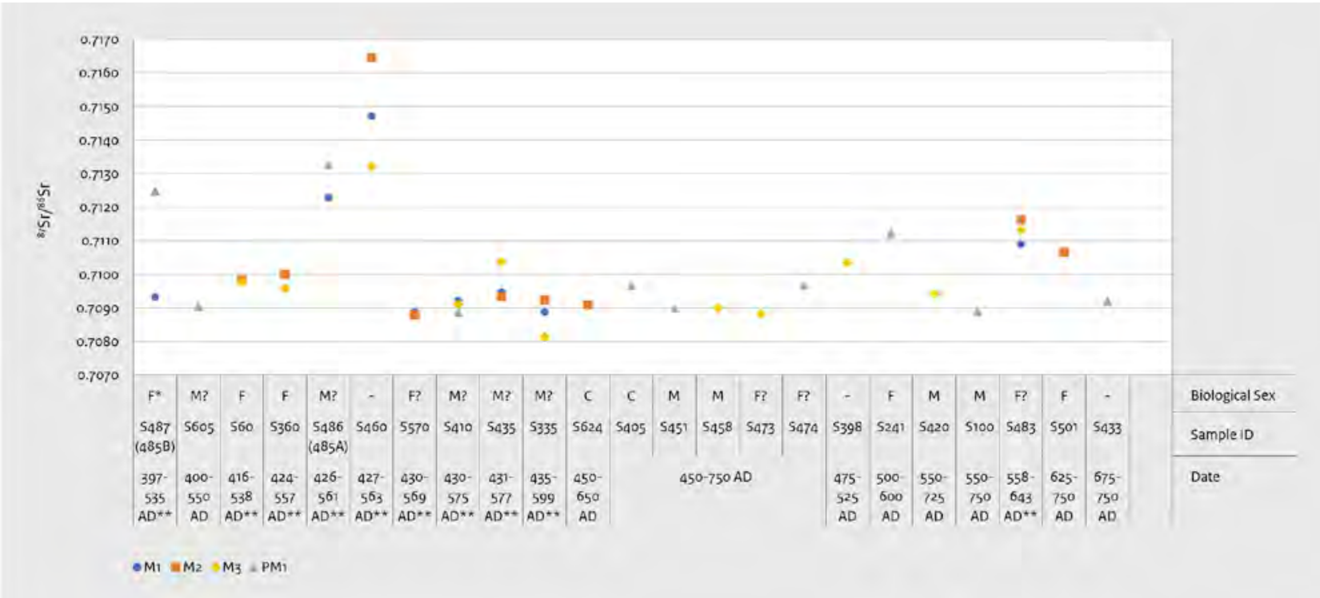

Figure 5.2. $^{87}Sr/^{86}Sr$ data from Oosterbeintum. Key: M1 – first molar; M2 – second molar; M3 – third molar; PM – premolar; Key: F – Female; M – Male; C – Child; * – biological sex based on aDNA; ** – ^{14}C dates.

AD. Although the number of data points is limited thereafter, the influx of individuals from different regions seems to stabilise (and be limited to a single region of origin?) until late 6th/ early 7th century AD.

Not only the geographical circumstances and geological (shallow) subsurface are equal, also the Sr data from Harlingen is comparable to that of Hogebeintum and Oosterbeintum. The Sr data range from 0.709277 (female, I3, AD 410-535) to 0.711403 (female, I5, AD 555-615). Except for individual 3, and possibly individual 1, all individuals exhibit $^{87}Sr/^{86}Sr$ that are not compatible with an origin in the Harlingen region. Similar to the other sites in Area 8, the heterogeneity in the Sr data is striking, possibly indicating various regions of origin. This is consistent with unpublished aDNA data that point towards a wide range of genetic origins of the Harlingen individuals.[138]

5.2.2 Area B: north-eastern inland area

The human combined Sr-O data from Area B, containing the sites of Zutphen, Elst (Utrecht), and Leusden, are presented in Table 5.5 and Fig. 5.3. The shallow subsurface geology of all these sites is somewhat comparable; they are located on or near the Utrechtse Heuvelrug, an ice-pushed ridge where the shallow geological subsurface is dominated by Pleistocene sediments. Consequently, if local arable lands were exploited, $^{87}Sr/^{86}Sr$ as high as circa 0.7110 can be expected.

The Sr data from the sites in Area B range between 0.708140 (Zutphen, male, 1331, AD 400) and 0.711968 (Leusden, G73-2-2, AD 550-710), the $\delta^{18}O_{PDB}$ values between −6.03 ‰ (Elst male, G174, AD 510-565) and −3.58 ‰ (Zutphen, male, 1331, AD 400).

The $^{87}Sr/^{86}Sr$ from the individual from Leusden, project Oud-Leusden, is relatively high compared to the current Dutch archaeological Sr isoscape (0.7110) and varies between 0.7113 and 0.7119. The intraindividual difference between the first and third molars ($\Delta^{87}Sr/^{86}Sr_{M1-M3}$ = 0.000601) can be interpret as childhood mobility. If the current Sr isoscape is accurate, the Sr data are also indicative for a non-local origin.

The combined Sr-O data from the male individual from Zutphen, named 'Gerward', undoubtedly point towards a non-local origin. More specifically, using the available reference data, the Sr ratio and the $\delta^{18}O_{PDB}$ value of the first molar (36) preclude an origin in the current Netherlands. The combination of data can be found in e.g., the United Kingdom, France, and Italy.[139]

Based on the local signal in the Elst region argued above, all but one (G238) $^{87}Sr/^{86}Sr$ are

[138] Pers.comm. E. Altena (FLDO), dd. August 2019.
[139] Essential baseline data from Germany is absent. Nevertheless, also Germany cannot be excluded as a possible region of origin.

Table 5.3. Combined Sr-O data from Oosterbeintum (n = 23 published earlier in McManus *et al.* 2013, n = 16 executed within the framework of this study).

Sample ID	Sex	^{14}C code	From	To	Element	$^{87}Sr/^{86}Sr$	Reference	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
S60	F	Ua–69995	416	538	37	0.709822	McManus *et al.* 2013	-	−7.08
			475	525	38	0.709781	This study	−4.51	−6.87
S100	M		550	750	35	0.708868	McManus *et al.* 2013	-	-
S241	F		500	600	25	0.711208	McManus *et al.* 2013	-	−6.00
S335	M	Ua–69996	435	599	36	0.708874	This study	−5.89	−9.13
			525	600	27	0.709232	McManus *et al.* 2013	-	−7.08
					48	0.708156	This study	−5.94	−9.22
S360	F	Ua–69997	424	557	46	0.710021	This study	−5.34	−8.23
			475	525	17	0.709993	McManus *et al.* 2013	-	−8.46
					38	0.709627	This study	−5.21	−8.02
S398	–		475	525	47	0.710330	McManus *et al.* 2013	-	−6.92
S405	C		450	750	25	0.709642	McManus *et al.* 2013	-	−6.62
S410	M	Ua–69998	430	575	36	0.709133	This study	−4.00	−6.03
			450	550	35	0.708824	McManus *et al.* 2013	-	−7.23
					38	0.709110	This study	−6.63	−10.35
S420	M		550	725	38	0.709404	McManus *et al.* 2013	-	−6.62
S433	–		675	750	45	0.709178	McManus *et al.* 2013	-	-
S435	M	Ua–69999	431	577	36	0.709475	This study	−4.76	−7.28
			550	700	47	0.709336	McManus *et al.* 2013	-	-
					38	0.710360	This study	−5.19	−7.99
S451	M		450	750	45	0.708961	McManus *et al.* 2013	-	-
S458	M		450	750	47	0.709026	McManus *et al.* 2013	-	-
S460	M	Ua–70000	427	563	36	0.714716	This study	−7.61	−11.96
			450	650	37	0.716448	McManus *et al.* 2013	-	-
					38	0.713206	This study	−6.60	−10.30
S473	F?		450	750	47	0.708828	McManus *et al.* 2013	-	−6.31
S474	F?		450	750	25	0.709657	McManus *et al.* 2013	-	−6.62
S483	F?	Ua–70001	558	643	46	0.710894	This study	−4.91	−7.53
			525	625	17	0.711630	McManus *et al.* 2013	-	−7.23
					38	0.711315	This study	−5.14	−7.91
S486 (485A)	M?	Ua–70002	426	561	26	0.712280	This study	−5.83	−9.04
			440	485	44	0.713245	McManus *et al.* 2013	-	−6.92
S487 (485B)	F*	024707P	397	535	36	0.709322	This study	−4.59	−7.01
			440	485	44	0.712460	McManus *et al.* 2013	-	−3.07
S501	F		625	750	37	0.710651	McManus *et al.* 2013	-	-
S570	F?	Ua–70004	430	569	26	0.708884	This study	−4.67	−7.14
			525	625	27	0.708791	McManus *et al.* 2013	-	−6.31
S605	M?		400	550	34	0.709000	McManus *et al.* 2013	-	−6.77
S624	C		450	650	27	0.709077	McManus *et al.* 2013	-	−5.38

The dates without ^{14}C codes are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.18 (average 0.08). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; C – Child; * – biological sex based on aDNA.

Table 5.4. Combined Sr-O data from Harlingen (Sr data published in Hielkema *et al.* 2017, O data generated within the framework of this study).

Sample ID	Sex	^{14}C code	From	To	Element	$^{87}Sr/^{86}Sr$	Reference	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
V172–M20–I1	F*	GrA–68001	545	600	33	0.709591	Hielkema *et al.* 2017	−13.27	−9.36
V175–M21–I2	F*	GrA–67994	430	540	18	0.709880	Hielkema *et al.* 2017	−12.75	−11.68
V177–M22–I3	F*	GrA–67995	410	535	28	0.709277	Hielkema *et al.* 2017	−14.61	−9.07
V214–M23–I5	F*	GrA–67997	555	615	26	0.711403	Hielkema *et al.* 2017	−15.50	−7.99
V257–M24–I6	F*	GrA–68000	540	600	16	0.710482	Hielkema *et al.* 2017	−15.60	−8.12
V258–M25–I7	F*	GrA–68002	405	535	13	0.710152	Hielkema *et al.* 2017	−13.49	−9.68

The dates without ^{14}C codes are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.18 (average 0.08). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; * – biological sex based on aDNA.

Table 5.5. Combined Sr-O data from Leusden, Zutphen, and Elst (n = 16, all executed within the framework of this study).

Site	Toponym	Sample ID	Sex	From	To	Element	$^{87}Sr/^{86}Sr$	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
Leusden	Oud Leusden	G73–2–2	–	550	710	M1	0.711968	−5.35	−8.25
						M2	0.711671	−5.03	−7.73
						M3	0.711368	−5.55	−8.58
Zutphen	Leesten de Enk	1331	M	400	400	36	0.708297	−3.58	−5.35
						47	0.708170	−4.67	−7.14
						48	0.708204	−5.44	−8.40
Elst	't Woud	G174	M	510	565	M1	0.711282	−5.36	−8.27
						M2	0.710756	−6.03	−9.37
						M3	0.710610	−5.78	−8.95
		G178	M	510	565	M1	0.709975	−5.02	−7.71
						M2	0.710172	−4.60	−7.02
						M3	0.710481	−5.54	−8.56
		G210	F	500	700	M1/2	0.710369	−5.07	−7.80
		G238	F	540	590	M1/2	0.712264	−4.77	−7.31
		G240	M	540	590	M1/2	0.710509	−5.14	−7.90
						M3	0.709303	−4.79	−7.34

The dates are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.17 (average 0.09). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; - – sex undetermined; M1/2 – first or second molar; M1 – first molar; M2 – second molar; M3 – third molar.

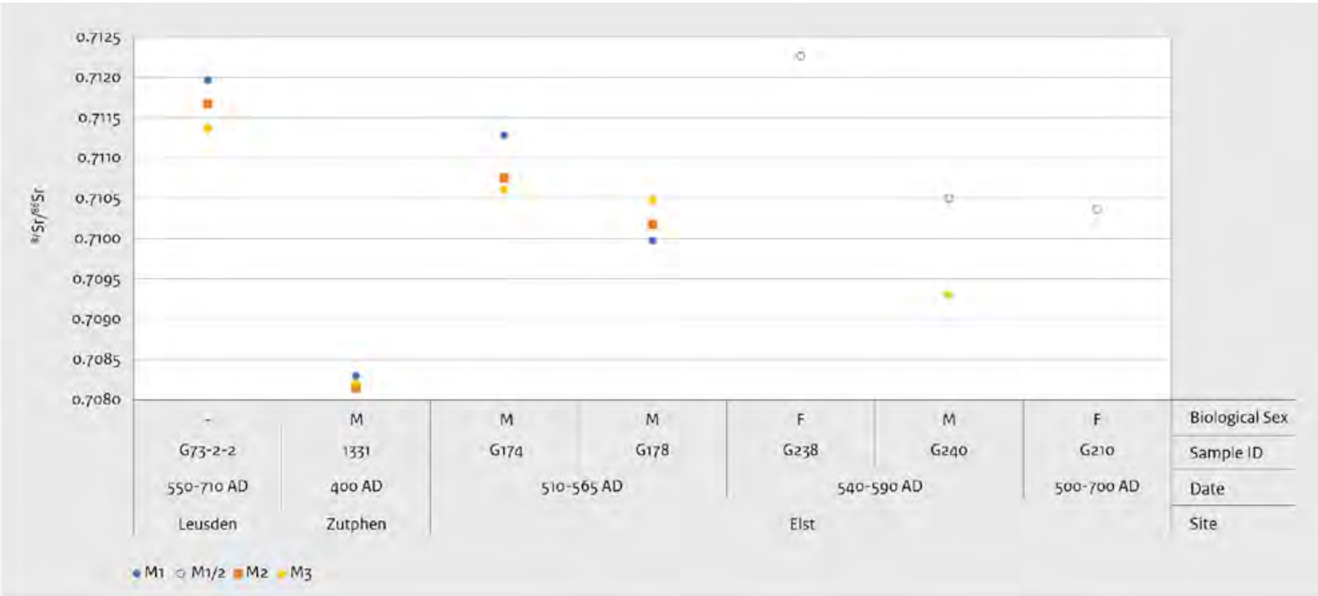

Figure 5.3. $^{87}Sr/^{86}Sr$ data from Leusden, Zutphen, and Elst. Key: F – Female; M – Male; - – sex undetermined; M1/2 – first or second molar; M1 – first molar; M2 – second molar; M3 – third molar; ** – ^{14}C dates.

compatible with the baseline $^{87}Sr/^{86}Sr$ range; similarly, all $\delta^{18}O_{PDB}$ values are comparable with the expected 'Dutch' range. Intra-individual (childhood) mobility is evident in the three males included in this study; G174, G178, and G240. For the females G10 and G238 too little data are available. If the argued baseline signature is accurate it would mean that the majority of this selected population is – possibly – of local origin.

5.2.3 Area C: western delta area

The generated Sr-O data from Area C, containing the sites of Rijnsburg, Leiden, and Oegstgeest, are presented in Table 5.6 and Fig. 5.4. To date, the variation in $^{87}Sr/^{86}Sr$ in the Holocene coastal region of the provinces Zeeland, South- and North-Holland has probably been mapped most accurately. Based on a substantial number of archaeological rodents from these regions, a conservative local $^{87}Sr/^{86}Sr$ signature of 0.7088-0.7095 was defined.

The Sr isotope data from the sites in Area C vary from 0.708018 (Oegstgeest, male, S2/2011-01, AD 600-700) to 0.710402 (Oegstgeest, female, S1/2012-01, AD 600-700), the $\delta^{18}O_{PDB}$ values range between –7.56 ‰ (Oegstgeest, female, S24/2012-02, AD 600-700) and –3.11 ‰ (Oegstgeest, male, S8/2012-01, AD 600-700). The data extremities are thus all connected to the 7th-century AD site of Oegstgeest Nieuw Rhijngeest-Zuid – SL Plaza.

The $^{87}Sr/^{86}Sr$ from Rijnsburg varies between 0.708417 and 0.710014. The lowest and highest ratios are incompatible with the local signature. The individuals that exhibit $^{87}Sr/^{86}Sr$ of 0.7087 (e.g., 1913 and E3.2+E4.2) are considered ambiguous; they can be indicative of residential mobility or stability. To avoid the overestimation of the number of non-local individuals, these ratios are considered to be compatible with the local $^{87}Sr/^{86}Sr$ baseline. Based on the combined Sr-O isotope data, individuals Lijk2.1-kind (child), Lijk 2.2-Volwassene 1 (female?), Lijk 5 (female), and Lijk 6 (female) may have spent their childhood in regions that are characterised by lower $^{87}Sr/^{86}Sr$ (Lijk 5) or higher $^{87}Sr/^{86}Sr$ (Lijk 6), or further inland (Lijk2.1-kind and Lijk 2.2-Volwassene 1). In total, for circa 45% of the investigated population (4/9) the Sr-O isotope data exclude origins in the region of Rijnsburg.

In contrast to the high number of non-local individuals in 7th-century Rijnsburg, neither of the individuals from Leiden Kop van Leeuwenhoek exhibit non-local Sr-O isotope ratios. In Oegstgeest on the other hand, all three selected individuals are of non-local origin. The oxygen isotope data are closely related to origins in the southern parts of Europe (e.g., Italy), as well as regions more inland (e.g., Germany). The 4 to 5 years old child (boy) S8/2011-01 (deposition H7)

Table 5.6. Combined Sr-O data from Rijnsburg, Leiden, and Oegstgeest (n = 3 published earlier in Van Spelde *et al.* 2021, n = 27 executed within the framework of this study).

Site	Toponym	Sample ID	Sex	From	To	Element	$^{87}Sr/^{86}Sr$	Reference	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
Rijnsburg	De Horn	1913	–	500	700	36	0.709134	This study	−5.67	−8.79
						37	0.708749	This study	−5.64	−8.73
		E3.2+E4.2	F	500	700	46	0.708761	This study	−4.41	−6.71
						37	0.708675	This study	−4.42	−6.73
						M3	0.708983	This study	−4.59	−7.00
		h1913/4.101	–	500	700	16	0.709374	This study	−5.67	−8.78
						17	0.709283	This study	−6.16	−9.57
		Lijk 2.1 – kind	C	500	700	16	0.709189	This study	−5.81	−9.01
						17	0.709033	This study	−7.45	−11.69
		Lijk 2.2 – Volwassene 1	F?	500	700	46	0.709133	This study	−6.88	−10.76
						47	0.709117	This study	−6.32	−9.84
		Lijk 2.3 – Volwassene 2	–	500	700	3/46	0.709428	This study	−5.15	−7.92
		Lijk 5	F	500	700	36	0.708417	This study	−6.78	−10.60
						37	0.708963	This study	−5.63	−8.71
						38	0.709222	This study	−7.00	−10.96
		Lijk 6 (= 3)	F	500	700	36	0.709987	This study	−5.99	−9.30
						37	0.710010	This study	−6.29	−9.79
						38	0.710014	This study	−6.31	−9.83
		E5 (No.14?)	C	500	700	M1	0.709037	This study	−6.22	−9.68
Leiden	Kop van Leeuwenhoek	KOL1768/Graf 1/ V270	M	500	700	26	0.709412	This study	−4.75	−7.27
						47	0.709125	This study	−5.42	−8.37
		KOL18/Graf 2	M	500	700	36	0.709106	This study	−6.29	−9.79
						37	0.709050	This study	−6.24	−9.71
Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza	S1/V2415/2012–01 (H1)	F*	600	700	16	0,710402	Van Spelde *et al.*, 2021	−5.55	−8.59
						47	0.710229	This study	−5.82	−9.02
						38	0.708935	This study	−5.11	−7.86
		S24/V2285/2012–02 (H2)	F*	600	700	46	0.709318	Van Spelde *et al.*, 2021	−6.45	−10.01
						27	0.709023	This study	−7.56	−11.88
						28	0.709518	This study	−6.38	−9.94
		S8/2011–01 (H7)	M*	600	700	73	0.708018	Van Spelde *et al.*, 2021	−3.11	−4.58

The dates are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.17 (average 0.09). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; - – sex undetermined; * – biological sex based on aDNA; M1 – first molar.

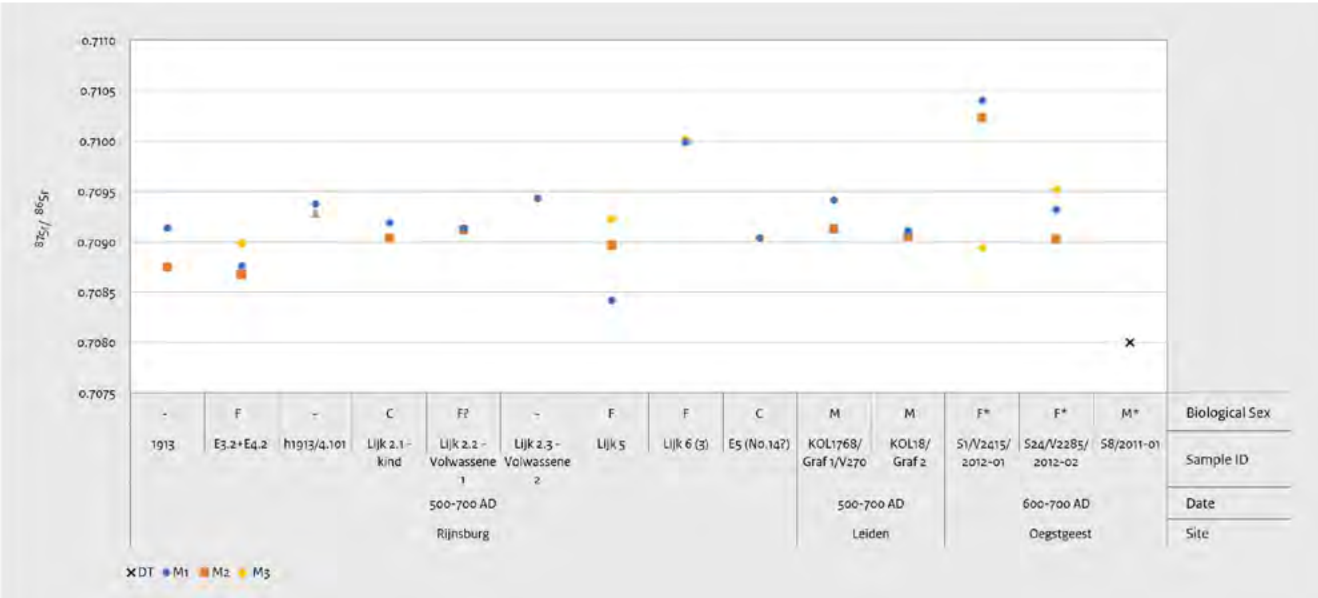

Figure 5.4. $^{87}Sr/^{86}Sr$ data from Rijnsburg, Leiden, and Oegstgeest. Key: DT – deciduous tooth; M1 – first molar; M2 – second molar; M3 – third molar; F – Female; M – Male; - – sex undetermined; * – biological sex based on aDNA; ** – ^{14}C dates.

exhibits the lowest strontium isotope ratio (0.7080) and the most positive $\delta^{18}O_{PDB}$ values (−3.1 ‰). For this individual, an origin in Italy or the French coastal region, is possible. Female S24/2012-02 (deposition H2) exhibits $^{87}Sr/^{86}Sr$ that are comparable to the local baseline signature; however, the $\delta^{18}O_{PDB}$ values are not. These negative $\delta^{18}O_{PDB}$ values (−7.5/−6.4 ‰) are indicative of an origin further inland; e.g., Hungary, Germany, but also France. The $\delta^{18}O_{PDB}$ data of S1/2012-01 (deposition H1) are compatible with a 'Dutch' origin; however, her Sr isotope ratios are not. The Sr isotope ratios of the first and second molar are too radiogenic and indicative of an origin on older, e.g., Pleistocene, sediments. Conversely, the $^{87}Sr/^{86}Sr$ of the third molar is compatible with the local Oegstgeest region. The isotopic shift between the second and third molar is indicative of mobility in childhood, the third molar's compatibility with the local $^{87}Sr/^{86}Sr$ signature may point to settlement in Oegstgeest between at around the age of circa 8 and 16.

5.2.4 Area D: central and eastern river delta

The generated Sr-O data from Area D, containing the sites of Houten, Bunnik, Wijk bij Duurstede, Zoelen, Ewijk, Lent and Nijmegen, are presented in Tables 5.7 and 5.8 and Figs. 5.5 and 5.6. Based on their geographical location, two groups were defined: Houten, Bunnik, and Wijk bij Duurstede are all located in close proximity of each other at the foot of the Utrechtse Heuvelrug opposite the river Rhine. If their food, and thereby their dietary strontium, was sourced on the flanks of this hill ridge, higher, i.e., more radiogenic, $^{87}Sr/^{86}Sr$ could be expected. However, an alternative scenario in which they used the nearby fertile river area for agriculture is more plausible.

The second group, comprising the Zoelen, Ewijk, Lent, and Nijmegen sites, is located in the eastern river delta amidst Holocene river sediments. Although alternative scenarios are possible, the use of the immediately surrounding fertile riverbank land for arable farming seems the most practical option for the Early Medieval inhabitants of Zoelen, Ewijk, and Lent.[140]

Consequently, for both groups, the dietary strontium is expected to range between 0.7088 and circa 0.7092/0.7095. However, Nijmegen is located on the higher Pleistocene sediments. Here, ratios exceeding 0.7095 may be expected as well.

The Sr data from the sites in group 1 from Area D vary from 0.708794 (Houten, skelet, AD 599-658) to 0.711932 (Wijk bij Duurstede,

[140] See Heunks & Van Hemmen 2016 for arguments for local arable farming in Lent.

Table 5.7. Combined Sr-O data from Houten, Bunnik, and Wijk bij Duurstede (n = 9 executed in the framework of a NWO funded project ('Tiel-Medel: vindplaatsen uit de Romeinse tijd'), n = 21 executed within the framework of this study).

Site	Toponym	Sample ID	^{14}C code	From	To	Sex	Element	$^{87}Sr/^{86}Sr$	Reference	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
Houten	Hoogdijk	Skelet	Ua–69927	599	658	–	36	0.709036	This study	−4.73	−7.23
							37	0.708948	This study	-	-
							38	0.708794	This study	−5.24	−8.08
Bunnik	Het Burgje	V137/INH5		390	600	F	16	0.7111220	Kootker *et al.*, in prep.	−4.35	−6.61
							37	0.711608	Kootker *et al.*, in prep.	−5.10	−7.84
							48	0.711912	Kootker *et al.*, in prep.	−5.54	−8.56
		V192/INH6		450	600	F*	46	0.709130	Kootker *et al.*, in prep.	−4.65	−7.11
							47	0.709106	Kootker *et al.*, in prep.	−5.02	−7.71
							38	0.709083	Kootker *et al.*, in prep.	−4.97	−7.63
		V228/INH7		450	600	M*	46	0.711850	Kootker *et al.*, in prep.	−4.42	−6.73
							47	0.710770	Kootker *et al.*, in prep.	−4.94	−7.58
							48	0.709690	Kootker *et al.*, in prep.	−5.37	−8.29
Wijk bij Duurstede	Veilingterrein	536–G8–IND1	KIA–32736	605	673	F	36	0.710962	This study	−6.24	−9.71
							37	0.711214	This study	−6.45	−10.06
							48	0.709234	This study	−8.12	−12.79
		1673–G1–IND4	SUERC–35889	650	780	F	46	0.709118	This study	−6.01	−9.34
							47	0.709281	This study	−6.10	−9.50
							48	0.709937	This study	−5.92	−9.18
		5376–G6–IND5	SUERC–35888	640	730	F	22	0.711932	This study	−6.38	−9.94
		5616–G4–IND6	Ua–38025	650	780	F	27?	0.709203	This study	−5.37	−8.28
		5788–G5–IND7	SUERC–34857	600	675	M	46	0.709268	This study	−5.27	−8.12
							47	0.709671	This study	−5.77	−8.93
							48	0.709147	This study	−5.91	−9.16
		5595–G3–IND8	Ua–38024	660	870	F	27	0.709399	This study	−5.38	−8.30
		5766–G7–IND9	Ua–38026	600	700	M?	36	0.708869	This study	−6.16	−9.57
							37	0.709161	This study	−6.16	−9.59
							38	0.708877	This study	−6.33	−9.86
		5034–IND10		–	–	M	36	0.709167	This study	-	-
							37	0.709208	This study	−6.18	−9.61
							38	0.709285	This study	−6.53	−10.20

Two samples (Skelet 37 and IND10 36) did not provide sufficient material for Sr and O isotope analysis. The dates without ^{14}C codes are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.16 (average 0.08). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; - – sex undetermined; * – biological sex based on aDNA; M1 – first molar.

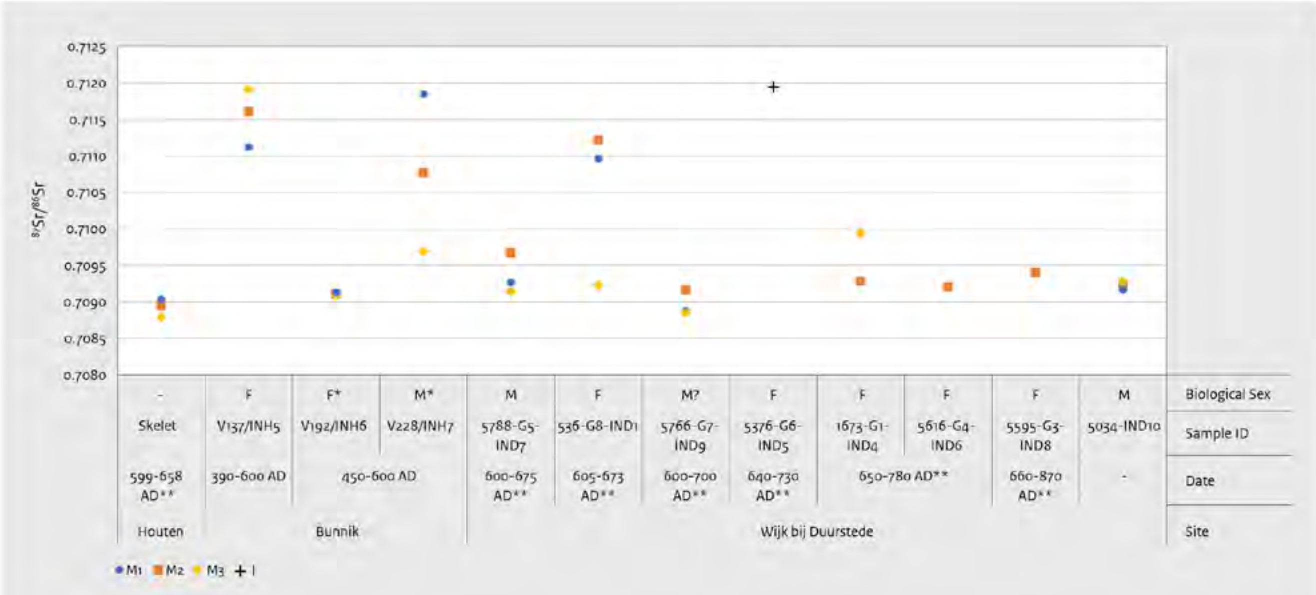

Figure 5.5. $^{87}Sr/^{86}Sr$ data from Houten, Bunnik, and Wijk bij Duurstede. Key: F – Female; M – Male; - – sex undetermined; DT – deciduous tooth; M1 – first molar; M2 – second molar; M3 – third molar; PM – premolar; ** – ^{14}C dates.

female, IND5, AD 640-730), the $\delta^{18}O_{PDB}$ values range between −8.12 ‰ (Wijk bij Duurstede, female, IND1, AD 605-673) and −4.35 ‰ (Bunnik, female, INH5, AD 390-600).

The combined Sr-O data from Houten are compatible with the lower range of the expected 'local' signal; nevertheless, no evidence of mobility is provided. The opposite is true for Bunnik. Two of the three individuals, a female (INH5) and a male (INH7) exhibit high $^{87}Sr/^{86}Sr$ that are incompatible with the baseline signature. Moreover, the isotopic differences between the dental elements (0.7111 to 0.7119 in INH5 and 0.7119 to 0.7097) indicate mobility during childhood; both individuals were residentially mobile between the ages of 3 and 8, and between 8 and 16 years of age. The Sr ratios are higher than the currently established baseline signatures in present-day the Netherlands. However, radiogenic signatures are expected in the boulder clay regions in the northeast of the Netherlands, as well as in certain regions in Wieringen and Texel (North-Holland). Recent research in Limburg also provides evidence that high $^{87}Sr/^{86}Sr$ are to be expected in the south.[141]

Two out of the eight individuals from Wijk bij Duurstede exhibit deviating $^{87}Sr/^{86}Sr$ and or $\delta^{18}O_{PDB}$ values. IND1, a female dated to the 7th century AD, has been residentially mobile during childhood; the shift between the first and second molar is limited ($\Delta^{87}Sr/^{86}Sr_{M1-M2}$ = 0.000253); however, the isotopic difference between the second and third molar may be considered significant $\Delta^{87}Sr/^{86}Sr_{M2-M3}$ = 0.001080). This is also evidenced by the $\delta^{18}O_{PDB}$ data. The shift in (geological source of) the diet between the ages of 3 and 8 years was not accompanied by a shift in water source. The shift between the second and third molars, on the other hand, did. The $\delta^{18}O_{PDB}$ of the third molar is very negative and not compatible with present-day the Netherlands. An origin more inland is quite plausible. Only one dental element was available from the second non-local individual, a late 7th/early 8th-century female (INH5). The $\delta^{18}O_{PDB}$ is not uncharacteristic, but the $^{87}Sr/^{86}Sr$ is higher than would be expected in the Wijk bij Duurstede region. A non-local origin matches the archaeological and osteoarchaeological evidence. She was interred in a prone position and was relatively tall compared to the rest of the female population (circa 173 cm compared to an average height of 163 cm).[142] A third individual, a female (IND4), exhibits Sr-O isotope data that are comparable with the local signature. However, the shift between the second and third molar is large and indicative of residential mobility (i.e., shift in diet/dietary Sr source) during childhood.

The botanical survey on Veilingterrein has shown that agricultural land was present in the

141 Veselka *et al.* 2021.
142 Panhuijsen 2012.

vicinity of the settlement; however, cereals may also have been imported at that time.[143] The majority of the Sr isotope data varies between 0.7088 and 0.7094, which is consistent with local agriculture in the river landscape.

Neither of the three 5th-century individuals from Zoelen and Ewijk exhibit Sr-O ratios that are compatible with a local origin. The high $^{87}Sr/^{86}Sr$ are more consistent with an origin in regions that are characterised by older, e.g., Pleistocene, subsurface sediments. Moreover, all three individuals show evidence of multiple migration events. Slight intra-individual variations in $\delta^{18}O_{PDB}$ are only observed in male individual INH2 from Ewijk.

If the majority of the dietary strontium was indeed sourced in the surrounding fertile riverbanks, ten out of the 21 selected individuals from Lent show deviating $^{87}Sr/^{86}Sr$ and/or $\delta^{18}O_{PDB}$ values (48%). The strontium isotope composition in male 1975/94 (AD 630-750) is compatible with the Holocene river sediments; however, the $\delta^{18}O_{PDB}$ values of the second and third molar are not. The negative ratios (–8.4/–8.7 ‰) preclude an origin in the Netherlands and the, for instance, the United Kingdom, but are consistent with an origin more inland. In addition, the shift in $\delta^{18}O_{PDB}$ between the first and second molar ($\Delta^{18}O_{M1-M2}$ = 2.17 ‰) indicates residential mobility (i.e., change of water source) after the age of 3. In theory, this individual may have been born in the Lent region, left around the age of 3, and returned to Lent after the age of 18. Similar $\delta^{18}O_{PDB}$ values are seen in the 7th-century possible male 1975/83. The shift in $\delta^{18}O_{PDB}$ is accompanied by a shift in $^{87}Sr/^{86}Sr$ (0.7092 to 0.7098). The $\delta^{18}O_{PDB}$ value of the first molar and the $^{87}Sr/^{86}Sr$ of the second and third molar are incompatible with the baseline signal for the Lent region. A combination of non-local Sr-O data is also found in the single dental element analysed from male 1975/82 (AD 630-750).

The remaining seven individuals are identified as non-locals based on their strontium isotope composition. Except for the 7th-century individual 1972/17, all $^{87}Sr/^{86}Sr$ are higher than the expected local signature. Interesting is individual 1972/17. Here, deciduous tooth 85 exhibits a relatively high $^{87}Sr/^{86}Sr$ of 0.7096. This dental element mineralises between 18 weeks *in utero* and 10 months of age, hence capturing the dietary Sr of the mother during pregnancy and the first 10 months after birth.[144] The first molar, which mineralises between birth and 3 years of age, displays a lower $^{87}Sr/^{86}Sr$ (0.7086). This difference can be interpreted as a shift in residence (soon) after pregnancy. The even lower $^{87}Sr/^{86}Sr$ of the second molar (0.7082) demonstrates a second change in residence, after the age of 3. While the first two ratios could be compatible with an origin in present-day the Netherlands, the latter (0.7082) excludes a 'Dutch' scenario. To date, ratios this low are extremely rarely found in human individuals; only in Oegstgeest (Area C) and Borgharen (Area F), where a 'foreign' origin seems to be the most accurate interpretation.

[143] Van Zeist 1990.
[144] Assuming that the children in early Medieval Lent were breastfed until 10 months and not yet weaned. Scientific data to verify this hypothesis is, to date, absent.

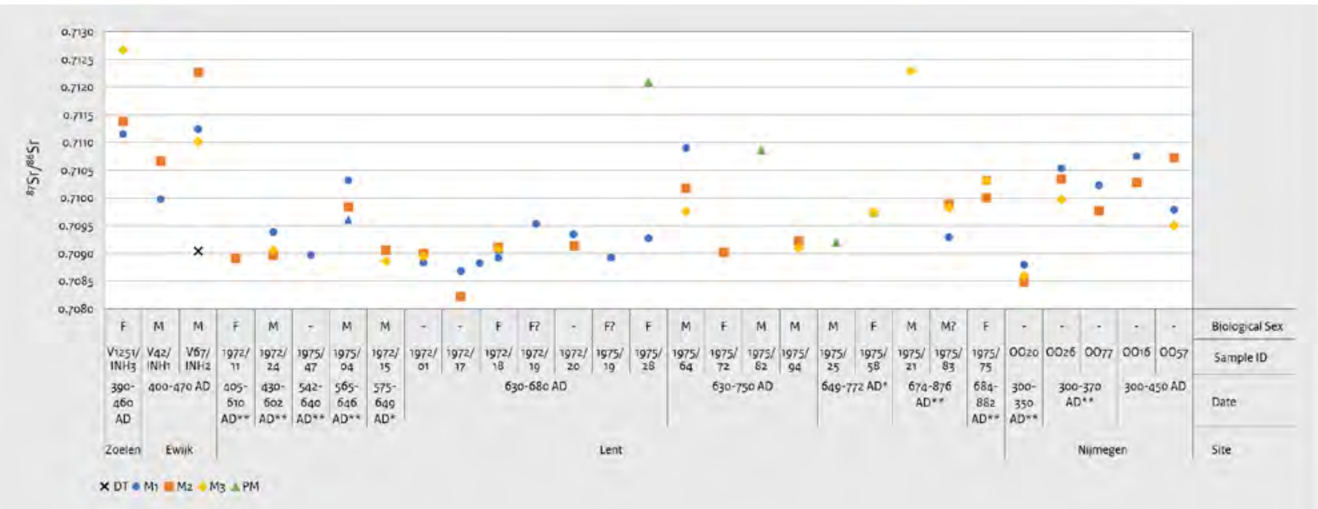

Figure 5.6. $^{87}Sr/^{86}Sr$ data from Houten, Bunnik, and Wijk bij Duurstede. Key: F – Female; M – Male; - – sex undetermined; DT – deciduous tooth; M1 – first molar; M2 – second molar; M3 – third molar; PM – premolar; ** – ^{14}C dates.

Table 5.8. Combined Sr-O data from Zoelen, Ewijk, Lent, and Nijmegen (n = 5 executed in the framework of a NWO funded project (‘*Tiel-Medel: vindplaatsen uit de Romeinse tijd*’), n = 61 executed within the framework of this study).

Site	Toponym	Sample ID	^{14}C code	From	To	Sex	Element	^{87}Sr/^{86}Sr	Reference	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
Zoelen	Scharenburg	V1251/INH3		390	460	F	36	0.711150	This study	−6.42	−10.00
							37	0.711379	This study	−6.36	−9.91
							38	0.712670	This study	−6.25	−9.73
Ewijk	Keizershoeve	V42/INH1		400	470	M	46	0.709979	Kootker *et al.*, accep.	−5.61	−8.68
							47	0.710662	Kootker *et al.*, accep.	−5.41	−8.35
		V67/INH2		400	470	M	26	0.711241	Kootker *et al.*, accep.	−4.87	−7.47
							27	0.712264	Kootker *et al.*, accep.	−5.41	−8.35
							28	0.711013	Kootker *et al.*, accep.	−5.86	−9.09
Lent	Azaleastraat	1972/01		630	680	–	16	0.708838	This study	−6.14	−9.55
							17	0.708990	This study	−6.12	−9.52
							28	0.708954	This study	−6.11	−9.50
		1972/11	Ua-69987	405	610	F	47	0.708914	This study	−5.77	−8.95
		1972/15	GrM-19026	575	649	M	36	0.709068	This study	−5.78	−8.96
				630	680		47	0.709058	This study	−5.98	−9.28
							18	0.708857	This study	−5.66	−8.76
		1972/17		630	680	–	85	0.709604	This study	−4.98	−7.64
							26	0.708681	This study	−5.98	−9.28
							27	0.708237	This study	−5.72	−8.86
		1972/18		630	680	F	16	0.708929	This study	−5.65	−8.74
							17	0.709109	This study	−7.37	−11.56
							18	0.709079	This study	−6.42	−10.00
		1972/19		630	680	F?	26	0.709533	This study	−6.35	−9.89
		1972/20		630	680	–	46	0.709343	This study	−6.28	−9.77
							47	0.709136	This study	−6.27	−9.77
		1972/24	GrM-19027	430	602	M	26	0.709387	This study	−4.96	−7.61
				630	680		27	0.708977	This study	−5.84	−9.05
							28	0.709058	This study	−6.36	−9.90
		1975/04	Ua-69988	565	646	M	36	0.710318	This study	−4.63	−7.07
				630	750		37	0.709835	This study	−4.94	−7.57
		1975/19		630	680	F?	75	0.709068	This study	−5.66	−8.76
							16	0.708924	This study	−6.19	−9.64
		1975/21	Ua-69989	674	876	M	48	0.712291	This study	−6.49	−10.12
		1975/25	Ua-69990	649	772	M	PM	0.709197	This study	−5.85	−9.07
		1975/28		630	680	F	46	0.709272	This study	−5.14	−7.92
							45	0.712090	This study	−4.89	−7.50
		1975/47	Ua-69991	542	640		72	0.709037	This study	−4.40	−6.69
				630	750	–	36	0.708972	This study	−6.90	−10.80
		1975/58	Ua-69992	649	772	F	45	0.709726	This study	−5.87	−9.10

Table 5.8. continued

Site	Toponym	Sample ID	^{14}C code	From	To	Sex	Element	$^{87}Sr/^{86}Sr$	Reference	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{DW}$ (‰)
				630	750		48	0.709744	This study	−5.73	−8.87
		1975/64		630	750	M	46	0.710901	This study	−5.34	−8.23
							47	0.710169	This study	−6.35	−9.89
							48	0.709755	This study	−4.50	−7.67
		1975/72		630	750	F	47	0.709021	This study	−3.92	−5.91
		1975/75	Ua-69993	684	882	F	46	0.710320	This study	−5.47	−8.44
				663	750		47	0.710002	This study	−5.98	−9.29
							48	0.710312	This study	−6.10	−9.48
		1975/82		630	750	M	35	0.710865	This study	−7.35	−11.52
		1975/83	Ua-69994	674	876	M?	16	0.709290	This study	−8.04	−12.66
				630	750		37	0.709884	This study	−6.12	−9.51
							38	0.709828	This study	−6.62	−10.33
		1975/94		630	750	M	46	0.709168	This study	−6.24	−9.71
							47	0.709209	This study	−8.41	−13.27
							48	0.709100	This study	−8.74	−13.81
Nijmegen	Hugo de Grootstraat	OO16		–	–	–	36	0.710753	This study	−7.27	−11.40
							37	0.710276	This study	–	–
		OO20		300	350	–	16	0.708796	This study	−4.09	−6.19
							17	0.708480	This study	−4.16	−6.31
							18	0.708596	This study	−5.16	−7.94
		OO26		300	370	–	36	0.710535	This study	−5.54	−8.56
							37	0.710338	This study	−5.21	−8.02
							38	0.709972	This study	−6.33	−9.85
		OO57		–	–	–	46	0.709789	This study	−4.47	−6.80
							47	0.710720	This study	−5.40	−8.34
							48	0.709502	This study	−5.38	−8.31
		OO77		300	370	–	16	0.710227	This study	−6.44	−10.04
							17	0.709766	This study	−6.23	−9.70

One sample (OO16, 37) did not provide sufficient material for Sr and O isotope analysis. The dates without ^{14}C codes are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.16 (average 0.08). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; - – sex undetermined; PM – premolar.

In addition to 1972/17, intra-individual mobility is seen in individuals 1975/04 (male, AD 565-646), 1975/28 (female, AD 630-680), 1975/64 (male, AD 630-750), 1975/75 (female, AD 684-882), and 1975/83 (male?, AD 674-876).

The Nijmegen data vary significantly between 0.7084 and 0.7102. The majority of the strontium isotope data, however, show high ratios of 0.7098 and higher (9/13, 69%). Although a scenario that almost all individuals are of non-local origin is possible, the use of different arable farmlands in the Nijmegen region (south of Lent) seems a more plausible alternative. The 4th-century individual OO20 exhibits the lowest $^{87}Sr/^{86}Sr$ that even precludes an origin the present-day the Netherlands. Moreover, the shift in $^{87}Sr/^{86}Sr$ between the dental elements are indicative of multiple migration events during the first 16 years of life. Remarkably, this is also seen in all other individuals from Nijmegen: OO16, OO26, OO57, OO77. This suggests that residential mobility, or shifting of the source regions of their food, played an important role in human life in the Early Medieval Lent and Nijmegen settlements.

5.2.5 Area F: southern inland area

The human combined Sr-O data from Area F, containing two archaeological sites in Borgharen, are presented in Table 5.9 and Fig. 5.7. Although the sites are in close proximity to each other, there is a striking difference in their dating. The individuals from Daalderveld date from the 3rd/4th to 6th century AD, while most of the individuals from Pasestraat are possibly a century younger.

The local strontium isotope signature is determined for the Borgharen region based on archaeological foxes and rodents (0.7104-0.7113).[145] However, more recent research using modern vegetation as a proxy for the local range of (ancient) bioavailable strontium isotope underlines the heterogeneity of the shallow subsurface in southern Limburg[146] and thus the complexity of characterising the dietary Sr sources used by the Late Roman/Early Medieval human populations. Therefore, the bioavailable Sr signatures in the Borgharen regions may have been more diverse than previously suggested, which may adjust the range up and/or down. Nevertheless, both studies show the presence of relatively high $^{87}Sr/^{86}Sr$, which can be connected to the older underlying subsurface sediments (loess).

The Sr isotope data range between 0.708210 (male?, S1066, AD 260-430) and 0.712087 (male, S822, AD 420-560), the $\delta^{18}O_{PDB}$ values between −8.56 ‰ (female, GI, AD 550-625) and −3.36 ‰ (female, S372, AD 400-540). Based on the expected local signature of 0.7104-0.7113, none of the individuals from Daalderveld could be identified as of possible local origin. Moreover, as stated above, the distribution in Sr data is immense. Neither the lowest ratios nor the highest $^{87}Sr/^{86}Sr$ are compatible with a 'Dutch' origin. In addition, intra-individual mobility is evident in all individuals from Daalderveld. The Daalderveld site represents a rare case of a seemingly complete population of non-local origin. More importantly, the areas of origin range from regions that are typified by very old geological subsurface sediments to more recent volcanic areas. The data strongly point to a pioneer population, first settlers, who came from several regions of Europe after the fall of the Roman Empire to establish a settlement in Borgharen, just north of Maastricht.

Following this first pioneering period, a more stable (local?) population is established in terms of origin. The Pasestraat Sr data vary between 0.7085 and 0.7108. At first sight this is a significant variation, indicative of multiple regions of origin. However, both extremes are found in one individual; female GIV (AD 550-625). Data from the first molar is absent, but the large isotopic difference between the second and third molar undoubtedly indicate residential

[145] Kootker *et al.* 2016.
[146] Veselka *et al.* 2021.

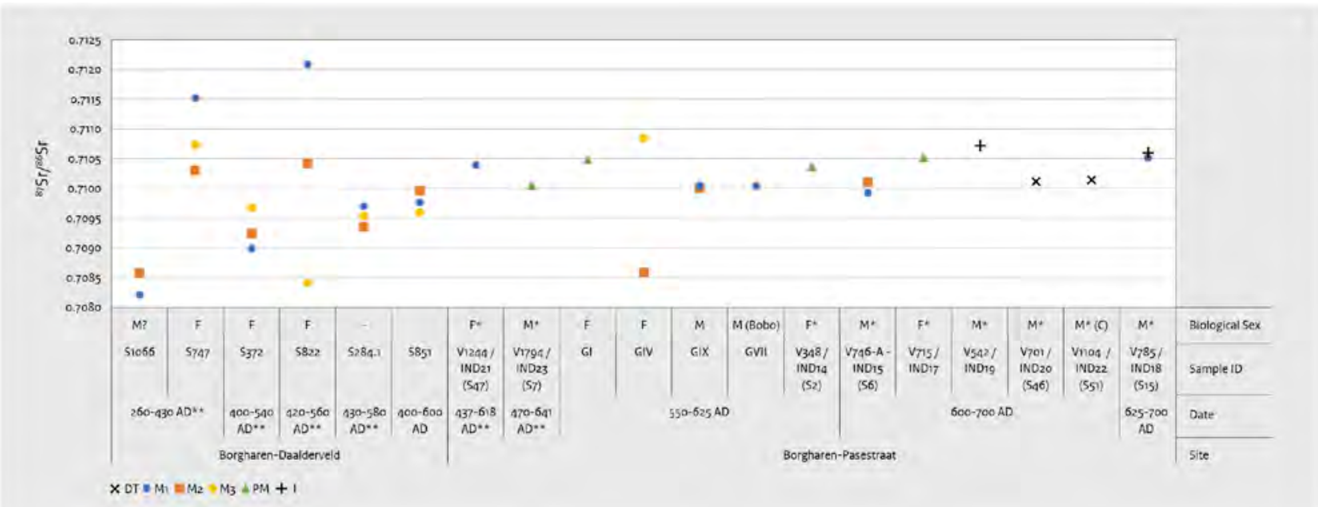

Figure 5.7. $^{87}Sr/^{86}Sr$ data from Borgharen. Key: F – Female; M – Male; - – sex undetermined; DT – deciduous tooth; M1 – first molar; M2 – second molar; M3 – third molar; PM – premolar; I – incisor; DT – deciduous tooth; * – biological sex based on aDNA; ** – [14]C dates.

Table 5.9. Combined Sr-O data from Borgharen (n = 15 published earlier, n = 19 executed within the framework of this study).

Toponym	Sample ID	Sex	^{14}C code	From	To	Element	$^{87}Sr/^{86}Sr$	Reference	$\delta^{18}O_{PDB}$	$\delta^{18}O_{DW}$
Daalderveld–Pasestraat	S1066	M?	Beta–321062	260	430	36	0.708210	Kootker, 2013	−5.78	−8.95
						47	0.708580	This study	−5.57	−8.62
	S284.1	–	Beta–321065	430	580	46	0.709707	Kootker, 2013	−4.54	−6.93
						47	0.709353	This study	−5.27	−8.12
						18	0.709541	This study	−3.73	−5.59
	S372	F	Beta–321064	400	540	46	0.708989	Kootker, 2013	−3.90	−5.88
						47	0.709245	This study	−4.40	−6.70
						48	0.709678	This study	−5.67	−8.78
	S747	F	Beta–321068	260	430	36	0.711520	Kootker, 2013	−4.32	−6.56
						47	0.710303	This study	−7.87	−12.39
						48	0.710733	This study	−5.88	−9.12
	S822	F	Beta–321070	420	560	26	0.712087	Kootker, 2013	−4.75	−7.28
						37	0.710415	This study	−6.47	−10.09
						28	0.708408	This study	−5.61	−8.67
	S851	M		400	600	46	0.709769	Kootker, 2013	−4.79	−7.34
						17	0.709961	This study	−5.99	−9.30
						1/28	0.709598	This study	−5.39	−8.32
Pasestraat 1995	GI	F		550	625	44	0.710478	This study	−8.56	−13.51
	GIV	F		550	625	27	0.708589	This study	−6.53	−10.18
						28	0.710849	This study	−6.33	−9.87
Pasestraat 1999	GIX	M		550	625	26	0.710051	This study	−4.89	−7.49
						37	0.710005	This study	−5.87	−9.10
	GVII	M (Bobo)		550	625	36	0.710050	This study	−5.87	−9.11
Pasestraat 2008	V348 / IND14 (S2)	F*		550	625	21	0.710359	Kootker, 2014	−4.33	−6.58
	V746–A – IND15 (S6)	M*		600	700	36	0.709928	Kootker, 2014	−5.75	−8.91
						37	0.710106	This study	−5.36	−8.26
Pasestraat 2009	V715 / IND17	F*		600	700	33	0.710515	Kootker, 2014	-	-
	V785 / IND18 (S15)	M*		625	700	36	0.710506	This study	−5.70	−8.82
						54	0.710595	Kootker, 2014	-	-
	V542 / IND19	M*		600	700	83	0.710716	Kootker, 2014	-	-
	V701 / IND20 (S46)	M*		600	700	I	0.710131	Kootker, 2014	−5.10	−7.84
Pasestraat 2012	V1244 / IND21 (S47)	F*	GrA – 55327	437	618	36	0.710396	Kootker, 2014	-	-
Pasestraat 2009	V1104 / IND22 (S51)	M* (C)		600	700	41	0.710146	Kootker, 2014	−4.72	−7.23
Pasestraat 2012	V1794 / IND23 (S7)	M*	GrA–55328	470	641	24/25	0.710050	Kootker, 2014	−5.69	−8.81

Two teeth from S747 did not provide sufficient material for Sr and O isotope analysis. The dates without ^{14}C codes are based on archaeological evidence. $^{87}Sr/^{86}Sr$ data are ± 0.000010 (2SE) or better, the 1SD of the $\delta^{18}O_{PDB}$ data is better than 0.11 (average 0.07). Element notation conform to FDI (Fédération Dentaire Internationale). Key: F – Female; M – Male; - – sex undetermined; * – biological sex based on aDNA.

mobility during her childhood. Given the incompatibility of the third molar's $^{87}Sr/^{86}Sr$, she settled in Borgharen after the age of 16. In addition to GIV, also the 6th/early 7th-century AD female GI is of non-local descent. In contrast to the seemingly 'local' $^{87}Sr/^{86}Sr$, the $\delta^{18}O_{PDB}$ value points towards an origin further inland.

Significant shifts between dental elements are not seen in any of the other Pasestraat individuals. Whether the individuals with an Sr ratio lower or higher than 0.7104-0.7113 are of non-local origin or not, the variation in the data is significantly less than in Daalderveld, which could be tentatively interpreted as a decrease in the influx of settlers from abroad and a stabilisation and perhaps even establishment of the 'local' Borgharen population.

Part IV

Synthesis

6 Human mobility in the Low Countries in the post-Roman period (5th-7th century)

6.1 Introduction

The geography of the Netherlands, dominated by lowland plains on either side of a river delta, has greatly influenced the life histories of the people who lived there. Large rivers facilitate transport[147], but, on the other hand, impede crossing. It is therefore hardly surprising that our delta of the rivers Rhine, IJssel, Waal, and Meuse separated cultural groups in most periods of (pre)history.[148] In this synthesis, the results of the isotopic analysis presented in the previous chapter are interpreted and contextualized in their chronological[149] and geographical context. Existing views regarding human mobility, mainly based on cemetery research, but also including settlement archaeology with a bird's eye view, form the basis for this contextualisation. The demographic trends sketched in this contextualisation have been observed before,[150] but are presented here with a little more detail, plus suggestions of what the possible explanation behind the trends may be.

6.2 Prelude: from prehistory to the Middle Roman period

In the Bronze and Iron Age, networks from Eastern Europe and Scandinavia extended to the part of the Netherlands north of the Rhine, while the Hallstatt and La Tène material culture from the Alpine area and present-day France occurs in the area up to the Rhine, including the southern Netherlands.[151] This was no absolute barrier: southern material culture was occasionally moved northwards and northern material culture may have reached the south, but, when seen from a Europe-wide perspective, the Lower Rhine Delta is indeed the area of a clear dividing line.

Although it is highly likely that Julius Caesar's Gallic Wars brought him to the Low Countries,[152] it is very hard to prove that by archaeological means. Therefore, it is a long tradition in the Netherlands to date the start of the Roman Period to the Augustan period. Emperor Augustus endeavoured to extend the Empire to the river Elbe, which, if successful, would then have included the entirety of the plains on either side of the delta. The result of this policy was that the northern part of present-day Netherlands was part of the Empire for a short time.[153]

Costly military defeats forced the authorities to accept the Rhine as *de facto* end of the Empire. In the course of the 1st century AD, extensive infrastructural networks of roads, watchtowers, fortifications, cities, and waterworks were created *ex nihilo*: the *limes*. At first, the function of this *limes* was a guarded transport infrastructure, supporting military advance. However, in the 2nd century its function changed and it became a defensive perimeter against attacks by Germanic groups living in the north.[154] South of the Rhine, the Roman authorities imposed an administrative structure in which tribal groups each had their own district (*civitas*) with capital city and supporting countryside. The *civitates* along the Lower Rhine, as well as the sandy area of the southern Netherlands and Flanders, were part of the province of Gallia Belgica at first and formed a new province of Germania Inferior from the late 1st century AD onwards.[155]

Regarding the civilian population, the north and south divide is clearly visible in these first three centuries AD. The habitation history of rural settlements, as well as house building traditions, suggest continuity in the north and discontinuity in the south. In the south (areas D and F in this study), the Late Iron Age and the Early Roman house types show considerable differences. It is a possibility that upheavals in the Caesarian period (mid-1st century BC), followed by immigration in the Augustan period, were responsible for this.[156] In the subsequent Augustan-Tiberian period (27 BC-37 AD), more and more evidence (house types, pottery, metal finds, and isotope analysis of faunal species) supports the immigration of various groups of people, of various origins, to the Dutch river area, leading to an increased understanding of the complexities behind the process of ethnogenesis.[157] The settlements in the southern part of the Netherlands in this period usually consist of one to three households, in rare cases up to six contemporaneous farmyards.[158] In the 3rd century AD, another phase of near complete abandonment of the southern sandy soils and a considerable depopulation of the central river area is observed, based on the settlement evidence, mainly dendrochronological dates

147 Van Lanen *et al.* 2015.
148 Vos *et al.* 2020.
149 The isotope data in this Chapter are presented in three dating groups, being the early and middle part of the 5th century, the late 5th and 6th century, and the 7th century. In a few instances, choosing the overlap between artefactual date and wide radiocarbon date would result in a narrow date at the start of the possible date range. In combination with known plateaus of the radiocarbon wiggle dates, this can be unsatisfactory. Burials dated in the early 5th century usually have a ^{14}C date in the plateau ranging from the late 3rd or early 4th into the early 5th century. There is a second date range (plateau) that often appears, ranging from the second quarter of the 5th century into the mid-6th century. There are a few cases where material culture of the early- and mid-5th century (Oosterbeintum burial 60 and 485A) appears in combination with the second plateau. A choice could be to date these burials to the overlapping middle part of the 5th century. However, the striking date of the second plateau is a good indication for a later date. Moreover, there are good arguments for older material culture ending up in younger graves (Kars 2011, 13-62). To summarize, in case of long date ranges of burials, the ^{14}C date range is preferred above artefact dates; secondly, younger dates are preferred over older in case of conflicts and when the need for choosing between periods arises.
150 Groenewoudt & Van Lanen 2018.
151 Louwe Kooijmans *et al.* 2005 for general developments; Heeren & Feijst 2017, 27-40 for material culture distribution maps of prehistoric material.
152 Roymans 2019.
153 Polak & Kooistra 2013.
154 Graafstal in prep.
155 Bogaers 1972; Raepsaet-Charlier 2002-2003.
156 Roymans 2019.
157 Habermehl *et al.* in press.
158 For instance, Heeren 2009; Hiddink 2005; Vos 2002; Wesseling 2000.

from water wells as well as pottery from the settlements.[159]

In central the Netherlands north of the Rhine and the eastern Netherlands (area B), on the other hand, different patterns emerge. To start with, a more or less continuous house building tradition is observed from the Roman into the Medieval Period.[160] Settlements of the 1st century AD are hard to grasp archaeologically, but seemingly new foundations of the later 1st or 2nd century continue to grow throughout the 2nd to the 4th century. Already in the 3rd century they are much larger than their counterparts in the south: from about six to ten contemporaneous farmyards.[161] In the Groningen-Frisian coastal area (area A) nearly all terp settlements seem to end in the 3rd century as well.[162] The paragraph below elaborates on this discontinuity, in relation to younger layers.

6.3 The Late Roman Period

When referring to the Late Roman Period in the chronological sense it is important to separate the better part of 4th century (circa AD 300 to AD 390) on the one hand, and the very late 4th and much of the 5th century (circa AD 390 to AD 470) on the other. Apart from Nijmegen, with a Late Roman garrison at the Valkhof and two large cemeteries spanning the late 3rd to the mid-5th century,[163] it is hard to find numerous Late Roman finds dating to the 4th century along the *limes* and in the southern Netherlands. In contrast, archaeological evidence dating to the 5th century is often found, in the form of human burials and single finds. Rural settlement features are scarcer, but certainly present.

The seemingly static military situation of the *limes* as a guarded line lasted until the late 3rd century (approximately AD 293), when the Roman authorities re-ordered the provinces. The *limes* remained in place, although there were probably far fewer fortifications manned and probably smaller garrisons. *Limes* remains dating to the Late Roman Period are scarce outside Nijmegen.

As sketched above, the provincial area south of the Rhine (areas D and F) was depopulated in the 3rd century. The Late Roman province, now called Germania Secunda, held only two *civitates*: the area of Tongeren and that of Cologne, the provincial capital. North of the road Heerlen-Maastricht-Tongeren, the countryside was nearly completely deserted. In area D, the eastern River area (between Tiel and Nijmegen) as well as around Cuijk and Gennep, some exceptions occur.[164] The same is true for area E where one single settlement dating to the 4th century is known on the coastline in Grijpskerke-Aagtekerke.[165] Inland parts of Zeeland are uninhabited in this period, due to severe flooding events.[166]

A re-population of the countryside in areas D and F is visible in the decades around AD 400: a few small settlements of no more than one or two farmyards, are known to date to that period. They seem to be small, and rather short-lived. Several seem to end again after one generation, although others might have been in use a little longer.[167] Moreover, the house plans, outbuildings, and handmade pottery exhibit a style commonly found in the provinces of Overijssel and Drenthe, and possibly other northern areas.[168] In the same area as the settlements, a small number of inhumation graves from this period around AD 400 are positioned among cremation graves from over a century earlier. It seems that these former burial grounds are selected purposefully by the Late Roman communities that inhabited this area.[169]

As already touched upon, the settlements of the central and eastern Netherlands north of the Rhine (area B) did not experience the decline in population seen in the 3rd century elsewhere, and they continue to flourish throughout the 4th century. They reach their largest extent in the late 4th century, with as much as eight to possibly twelve contemporaneous farmyards.[170] However, after their *floruit* in the late 4th century, archaeological evidence reveals a decline in size in the 5th century. Most of them disappear altogether around the middle of the 5th century; a few continue to exist, but markedly smaller in size.[171]

In the Groningen-Frisian coastal region (area A) several terp settlements are reinhabited as well. Cultural layers dating to the 5th century are found on top of those of the 3rd century,[172] although exceptions occur, such as Ezinge where evidence of 4th-century activity is found.[173] Interestingly, this pattern of depopulation in the 4th century and re-population in the 5th seems to fit the pattern observed in the Roman province, rather than that of the central/eastern

159 Heeren 2015; Roymans, Derks & Heeren 2020.
160 Huijts 1992; Waterbolk 2009.
161 Van der Velde 2011, 81-144; Taayke *et al.* 2012.
162 Nicolay 2014, 37; Nicolay *et al.* 2018.
163 Steures 2012; Van Enckevort & Thijssen 2014.
164 Van Enckevort, Hendriks & Nicasie 2017, 94-117, 236-240.
165 Delporte *et al.* 2011.
166 Van Dierendonck 2012; Pierik 2017, 69-72, 203-217.
167 Heeren 2017; Van Enckevort, Hendriks & Nicasie 2017, 94-122.
168 Heeren 2017.
169 Heeren 2009, 211-213, 235; see also Chapter 3 for examples investigated here.
170 Taayke *et al.* 2012; Van der Velde 2011, 79-144.
171 Van der Velde 2011, 147-148; Taayke *et al.* 2012, 291-297; Van Enckevort *et al.* 2017, 79-94, 236-240.
172 Nicolay 2014, 17, 37; Nicolay *et al.* 2018.
173 Nieuwhof 2016.

Netherlands north of the Rhine. What the reasons may be behind this remains to be determined: close economic ties with and dependence on the Roman province could be a possible explanation, but regional circumstances, such as problems with water management, are possible as well.

With regard to the origin of the new settlers in the northern coastal area, there are indications based on the cultural findings. Nicolay *et al.* point to the fact that cross-headed brooches dating from the second quarter of the 5th century onwards are regularly found in this area.[174] This is a style originating in Scandinavia and northern Germany and spreads to Groningen/Friesland and eastern England later. These brooches, as well as so-called Anglo-Saxon pottery, are often believed to be related to Anglo-Saxon groups populating the shores of the North Sea.[175]

A little more can be said about the reasons for the particular pattern that the coastal region and the southern Netherlands experience repopulation, while area B, the middle and eastern Netherlands north of the Rhine, seem to be (almost) suddenly deserted. One possibility is that this apparent decline was rather limited, in the sense that settlement locations were abandoned and others were founded in other parts of the landscape. One could hypothesise that due to climatic circumstances or other modes of production, the population preferred other parts of the landscape; therefore, the abandonment of settlements does not necessarily represent an actual depopulation. The fact that a more or less continuous house building tradition is known here could support such a view.[176] However, corresponding settlements founded at the same time as the termination of the excavated large ones, are not readily available. Having said this, it is at this moment still a challenging task to date settlements with high accuracy and precision.

Another possibility is that of emigration: it is highly likely that (parts of) the population migrated south, especially since the domestic architecture and ceramic style of the settlements found in the former Roman province in the first half of the 5th century exhibit characteristics belong to our area B (see above).

The cemeteries in use from the early 5th century onwards do not really help to choose between these options. In the central and eastern river area, large cemeteries like Elst-'t Woud, Rhenen-Donderberg, and Wijchen-Centrum have been found.[177] The earliest graves from these cemeteries date to the early 5th century and burials from the late or at least second half of the 5th century are present as well. However, this does not mean that the burial grounds were used continuously, and by one and the same burial community. There is a clear difference in burial location and orientation of the early 5th-century graves on the one hand (phase 1) and the late 5th-century burials (phase 2) on the other. Our chronological tools are not precise enough to establish whether phase 1 and 2 follow each other without interruption or that the sites were discontinued temporarily for approximately a few decades. Likewise, it is unknown whether a single burial community simply started to inter their dead in slightly different ways in another corner of the same cemeteries, or whether an existing cemetery was adopted by a new immigrant community after abandonment.

This migration from area B to area F and probably also area D is not only attested on the basis of settlement evidence. Study of gold circulation in these periods clearly attests that late 4th-century hoards, most likely paid by the Roman authorities to barbarian war leaders, are only found north of the Rhine, while the slightly later hoards of the period AD 395-413 are found both beyond and within the former *limes*.[178] Usurper Constantine III (AD 407-411) certainly played an important role in the payment of gold to foreign groups on both sides of the Rhine, but general Stilicho (AD 395-408) might have taken the first steps, probably allowing groups to settle in the province around AD 401-402.[179] This practice of gold payments to groups in the Rhine frontier lasted at least until the 460s.[180] After that time, a new situation arose.

While it is on the basis of the above very likely that a migration movement from area B to area F and D happened, the southern settlements are very small (one or two farmsteads) and rather short-lived. The one at Goirle-Huzarenwei seems to be inhabited for a single generation only; Alphen-Kerkakkers may have been use throughout the 5th century, although that is far from certain.[181] These settlements, consisting of one farmyard per generation or maybe two farmyards in a single habitation phase evoke the impression of a small-scale movement. The question remains where the rest of the population from the rather large settlements in area B went.

174 Nicolay *et al.* 2018.
175 Nicolay *et al.* 2018; Nicolay 2014, 30-31; Lanting & Van der Plicht 2009/2010, 122-150.
176 Huijts 1992; Waterbolk 2009; Cf. Van der Velde 2011, 147-148.
177 Elst: Verwers & Van Tent 2015. Wijchen: Heeren & Hazenberg 2010. Rhenen: Wagner & Ypey 2012.
178 Roymans 2017.
179 Roymans 2017.
180 Roymans & Heeren 2017.
181 Van Enckevort *et al.* 2017, 94-95, 101-102, with references.

From all the above we can conclude the following. Based on settlement archaeology and the chronology of burials, the 5^{th} century appears a highly dynamic period. Migration from distant areas across the North Sea to the coast of the northern Netherlands (area A) is suggested, and immigration from the Central Netherlands north of the Rhine and the Eastern Netherlands (area B) into the southern Netherlands (areas D and F) seems likely as well. However, many questions remain. The movement south seems to be small-scale and short-lived when looking at the immigrant settlements, whereas in the supposed area of origin, large discontinuities are observed. Influxes from other areas are possible and even highly likely, and we also should not rule out return migration or a continued move, in the sense that the people left for another destination after having lived at a certain settlement site for just a number of years.

6.3.1 Isotope analysis of 5^{th} century burials

The 5^{th} century AD was represented by 16 individuals from four different research areas (all but area C). Although high degrees of mobility were expected, it was still surprising to find all (100%) individuals exhibit a strontium and/or oxygen isotope composition that is incompatible with the expected local range based on the Kootker *et al.* publications (Figs. 6.1 and 6.2).[182] Moreover, almost 94% of the individuals within this group (n = 15) show shifts in strontium isotope composition that exceed 0.0002, and therefore are interpreted as intra-individual mobility, i.e., mobility during childhood between birth and circa 16 years of age.

This outcome of the study mirrors the archaeological-cultural narrative of the 5^{th} century outlined above; the isotope data verify the hypothesis that the 5^{th} century was a highly dynamic period in terms of mobility and migration.

6.4 The late 5^{th} and 6^{th} century

When compared to the dynamics observed in the previous period, the late 5^{th} and 6^{th} century seem rather stable in terms of settlement continuity. The general picture is that once new settlements had been founded in the late 5^{th} century, many of those remained in use throughout the 6^{th} century and even longer. Variations within areas are highlighted below.

[182] Kootker *et al.* 2016; 2019.

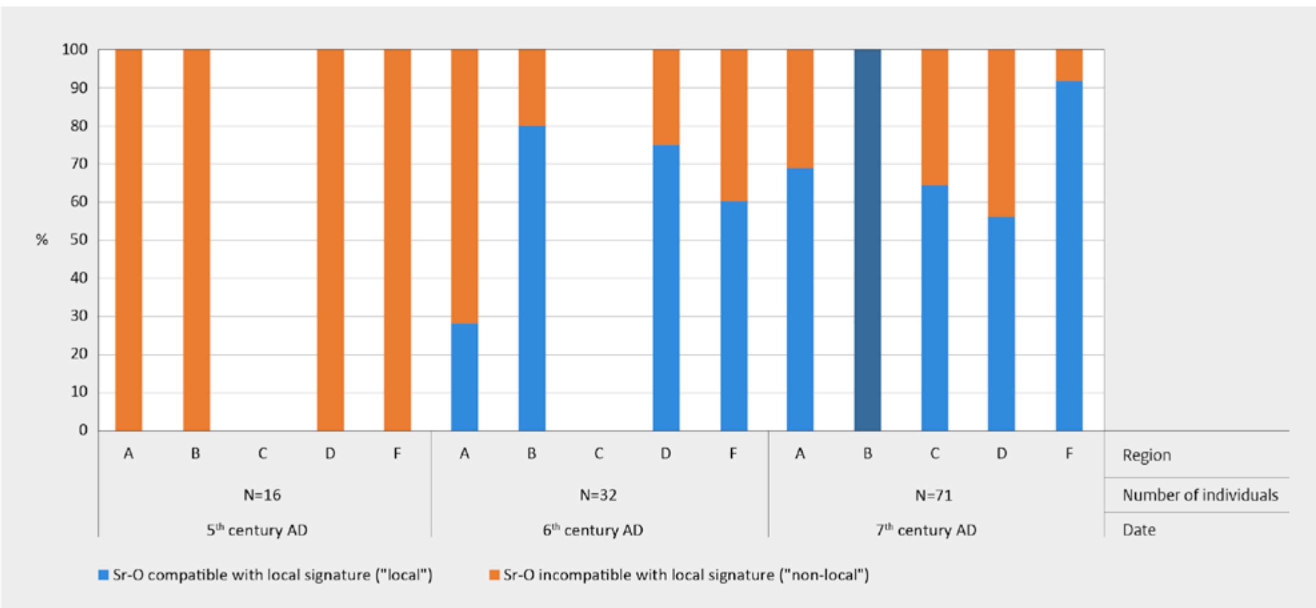

Figure 6.1. Overview of the ratio of 'possibly of local origin' versus 'definitely not of local origin' per time period and per study area. Total number of individuals included in this graph is 119. One individual (FM109) was excluded due to the absence of a relative of absolute dating. Key: dark blue: this study area contains only one individual.

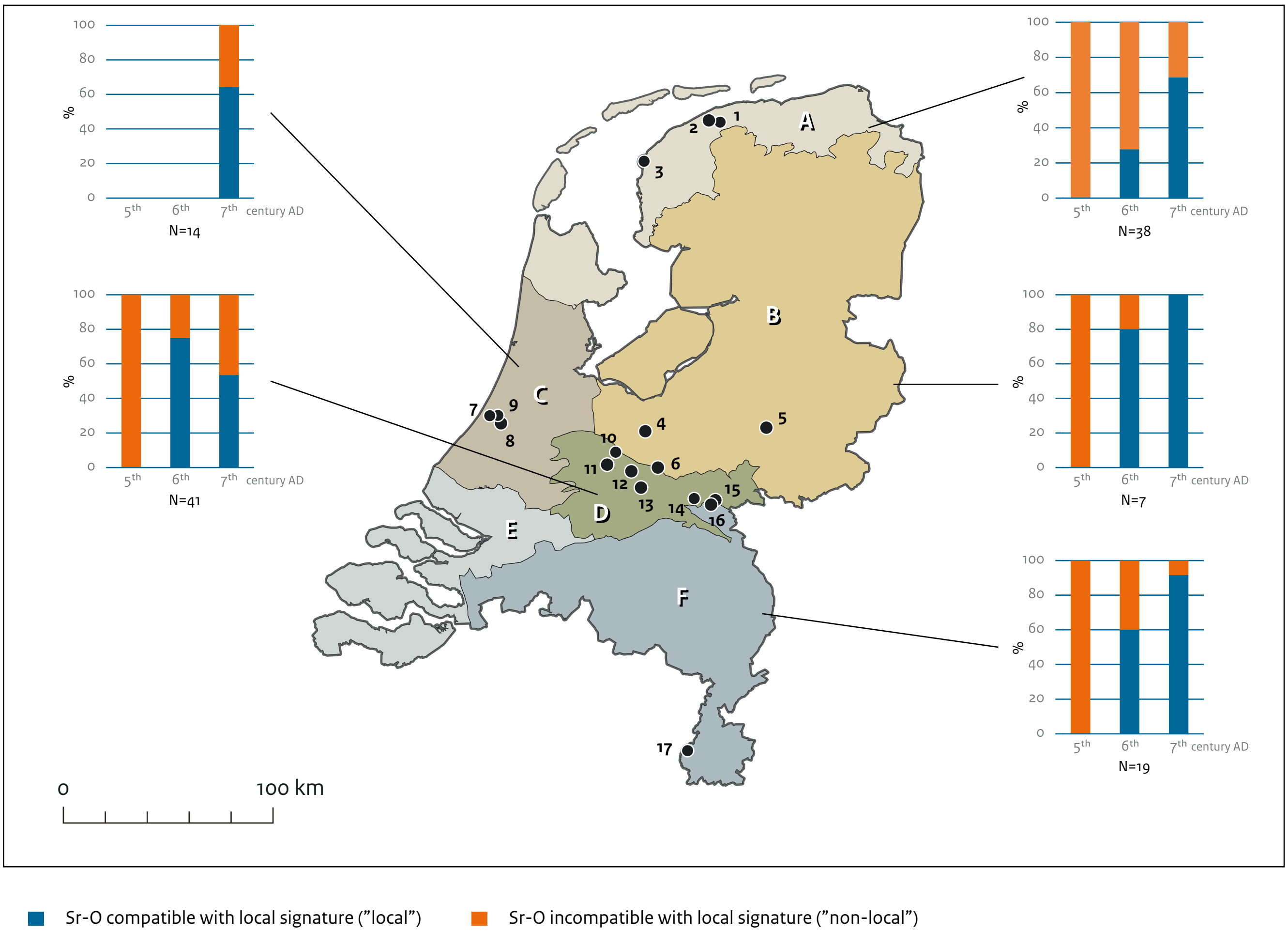

Figure 6.2. Map of the Netherlands with the Early Medieval sites included in this study with interpreted Sr-O isotope data per archaeological region and per time period. Total number of individuals included in this graph is 119. One individual (FM109) was excluded due to the absence of a relative of absolute dating. Key: 1 – Oosterbeintum; 2 – Hogebeintum; 3 – Harlingen; 4 – Leusden; 5 –Zutphen; 6 – Elst; 7 – Rijnsburg; 8 – Leiden; 9 – Oegstgeest; 10 – Odijk; 11 – Houten; 12 – Wijk bij Duurstede; 13 – Zoelen; 14 – Ewijk; 15 – Lent; 16 – Nijmegen; 17 – Borgharen. Figure by Marjolein Haars (BCL - Archaeological Support), modified after Fig. 3.4.

In the northern coastal zone (area A), some terp settlements were re-inhabited in the early 5th century (see above), others became inhabited in the late 5th or early 6th century; nearly all of these continued to be used throughout the Early Middle Ages and much longer as well.[183] Burial sites such as Oosterbeintum and Hogebeintum (Chapter 3) show the same chronology.

For area B, the middle and eastern Netherlands north of the Rhine, various authors claim that the discontinuity assumed before was not as deep as previously thought, and that a fair degree of continuity must be observed.[184] However, at the same time, it is hard to establish this on archaeological grounds. Single finds may date to the 'gap' of the second half of the 5th century, but excavated features are another matter. Settlement phases with clear habitation features dating to the later 5th century are nearly lacking, and the number of settlements founded around the start of the 6th century is limited.[185]

In the western delta area (area C) hardly any 4th and early 5th-century activity is archaeologically attested. Therefore, the appearance of new settlements (for instance Katwijk-Zanderij, Oegstgeest-Nieuw Rhijngeest) as well as burial sites (Rijnsburg-De Horn) in the later 5th and the early 6th century is clearly visible. [186] Many of these remained used throughout the Early Middle Ages. How this apparent archaeological discontinuity in the 4th and early 5th century relates to continuity suggested on the basis of

183 Nicolay 2014, 14-19, esp. Fig. 1.11.
184 Van der Velde 2011, 146-148, with references.
185 Van der Velde 2011, 146-162; Van Enckevort *et al.* 2017, 79-94, 236-240.
186 Dijkstra 2011; Dijkstra & De Koning 2017; Van Enckevort *et al.* 2017, 123-129.

Roman or even prehistoric toponyms is an issue still unresolved.[187] However, this theme falls outside the scope of this study.

The central and eastern river area (area D) show a more complex picture. As exceptions to the general picture of abandonment a few settlements, such as Nijmegen, Lent and Odijk, seem to be inhabited from the Middle and Late Roman Period onwards, uninterrupted, into the 6th century or even longer. While the added evidence of single finds and excavated features may result in this conclusion, it is important to state that when only looking at settlement features, this suggested continuity is hard to find. Moreover, the exceptions generally apply to former Roman (military) centres. New rural settlements are founded in the late 5th or often the early 6th century in especially the central river area.[188]

In area F, the southern inland area, more or less the same happened. In modern Limburg, relics of the Middle Roman Period are used again from the mid/late 5th century onwards, throughout later periods, or, new foundations from the same period occur.[189] Burial sites such as those at Borgharen (Chapter 3) show the same chronology. In the Meuse-Demer-Scheldt area, there is a discrepancy between settlement and burial evidence. Settlements like those of Breda-West (Steenakker and Huifakker) and Tilburg-Stappegoor are inhabited from the second half of the 5th century throughout the 6th into the 7th century. However, based on burial evidence alone, it was claimed that the area was colonised from around the mid-6th century onwards.[190] It remains to be seen whether the earlier communities left and new ones immigrated, or that burial customs changed and it is only the archaeological visibility that varies.

6.4.1 Isotope analysis of 6th-century burials

The 6th century AD is represented by double the number of individuals compared to the previous century (n = 32). Regrettably, no burials from area C dating to the 6th century are available; the ones with a broad date (6th - 7th century) are attributed to the latter period. Results for this period are shown in Figs. 6.1. and 6.2. During the 6th century, individuals that exhibited Sr-O isotope compositions that were comparable to the expected local signature were seen in all areas researched (n = 17, 53%). Intra-individual mobility is seen in fifteen individuals; six of them exhibit $^{87}Sr/^{86}Sr$ that are considered compatible with the local signal (three from Elst (B), one from Lent (D), and two from Borgharen (F)). This could either mean that the source of their food changed, or that they travelled between geographically different, but isotopically rather similar regions. In the latter theory, this could mean that they were of non-local descent as well, slightly decreasing the percentage of individuals of possible local origin in these research regions.

The archaeological sites included in areas A (Hogebeintum and Oosterbeintum) and F (Borgharen) are similar to the ones in the 5th century. Here, a first critical insight can be provided into the establishment of a settlement and the commissioning of a burial field by pioneering populations (5th-century data) and the gradual shift in demographic situation from an immigrant population to a hybrid immigrant-local population through adaptation and adjustment to their new environment (or local host community).[191]

6.5 The 7th century

Many settlements founded in the previous centuries (late 5th/early 6th century) continue to exist throughout the 7th century. At the same time, there are settlements ending in the late 6th century, such as Leersum-Middelweg and Utrecht-Terweide to name just some, and others being founded around AD 600, for instance Nistelrode-Zwarte Molen.[192]

More or less the same can be said for the burial evidence. Many cemeteries, from north to south, show a continuous use from the 5th to the first half of the 8th century. At the same time, newly founded cemeteries occur, such as Lent-Azaleastraat. Relevant here is that an older cemetery is known at a short distance, Lent-Lentseveld, which was in use from the late 5th to the late 6th century.[193]

An important question to be resolved through additional research is whether such newly started settlements and cemeteries are offshoots from already existing neighbouring

187 Dijkstra 2011, 80; Dijkstra & De Koning 2017, 60, Fig. 4.2.
188 Van Enckevort *et al.* 2017, 129-148, 236-240.
189 Van Enckevort *et al.* 2017, 117-121, 236-240.
190 Theuws 1988, 189-196; Theuws & Haperen 2012, 163.
191 McSparron *et al.* 2020.
192 Van Enckevort *et al.* 2017, 79-148, 236-240, with references.
193 Hendriks in prep.; Hendriks & Roode 2012.

communities who chose new sites in different places, for reasons we do not grasp, or whether these new sites represent newly immigrating groups of people from further away. The excavators of the Lent-Azaleastraat cemetery choose the latter explanation, based on the distant origin of the material culture (Middle-Rhine and Moselle area).[194] However, they clearly express doubt and the other option, that the objects came here through trade and exchange networks, was and is still on the table.

The picture is more complex, not confined to the newly started sites. The observation of much chronological continuity in the use of settlements and cemeteries (both in the late 5th/6th and in the 7th century) might evoke an association of stability within the communities using these sites, but this still does not tell us anything about the composition of the population. Theuws pointed our attention towards the fact that in demographic terms, many communities of the southern Netherlands were too small for self-sufficiency and independent reproduction on the long term.[195] Therefore, they must have interacted either in a regional framework, or over long distances, both for marriage partners and for exchange of goods. In other words, while the archaeology may imply stability, continued small-scale migration of marriage partners or other community members between people living in distant areas may have happened all the time.[196]

Above these small-scale movements, another supra-regional factor must be mentioned that probably influenced long-range mobility, and that is the political-military sphere. It has long been known that Frisian influence spread from the northern coastal regions to the western delta area (Rijnsburg and surroundings) and the central river area (Utrecht, Wijk bij Duurstede) in de 7th century, to be repelled by the Carolingian rulers in the 8th century. Nicolay recently summarized the development and the evidence behind it again, adding the evidence of precious metals.[197] For the 7th century, this means that mobility between our areas A and C is highly likely. At the same time goods from across the North Sea were traded to and from the Frisian coastal area. For more southern regions, mobility is a distinct possibility as well (see above), but is less well contextualised by historical evidence.

6.5.1 Isotope analysis of 7th century burials

The previously outlined picture of a hybrid society in which immigrants and people of possibly local origin live together can also be sketched for the subsequent period (Figs 6.1 and 6.2). In all areas, except research area B, a mix of people of possible local origin and people who certainly spent (part of) their childhood elsewhere is seen. The percentage of non-local individuals is decreasing compared to the 6th century. Area B, the north-eastern inland area, is represented by only 1 individual from Leusden (G73-2-2). Although the $^{87}Sr/^{86}Sr$ of the molars are somewhat on the high side, partly due to the 'local' $\delta^{18}O_{PDB}$ values, it was decided not to include this individual in the group of certain non-local origins.

Intra-individual mobility is seen in nineteen individuals; seven of them exhibit $^{87}Sr/^{86}Sr$ that were considered compatible with the local signal (two from Rijnsburg (C), and one from Leusden (B), Leiden (C), Houten (D), Lent (D), and Wijk bij Duurstede (D). The shift in strontium is associated with a change in food source, which may or may not be related to mobility.

6.6 Demographic trends

To start with, the complete dataset shows a more or less equal demographic composition of 50 female/female? individuals, 45 male/male? and 25 individuals of unknown sex (n = 120, n=119 included in Fig. 6.3). When breaking this down to the subsequent periods, interesting patterns emerge. In the 5th century, the 16 individuals of non-local origin shows a more or less equal division of five female/female?, six male/male? and five individuals of unknown sex. In the 6th century, females dominate the group of the non-local individuals (n = 17): ten female/female?, five male/male? and two of indeterminate sex. The 7th century-burials of non-local origin (n = 24) show more or less the same pattern: fifteen female/female?, seven male/male?, and two of indeterminate sex (Fig. 6.3).

194 Van Es & Hulst 1991, 219-222.
195 Theuws 1988, 189-196.
196 Theuws 1988, 189-196.
197 Nicolay 2014, 20-27.

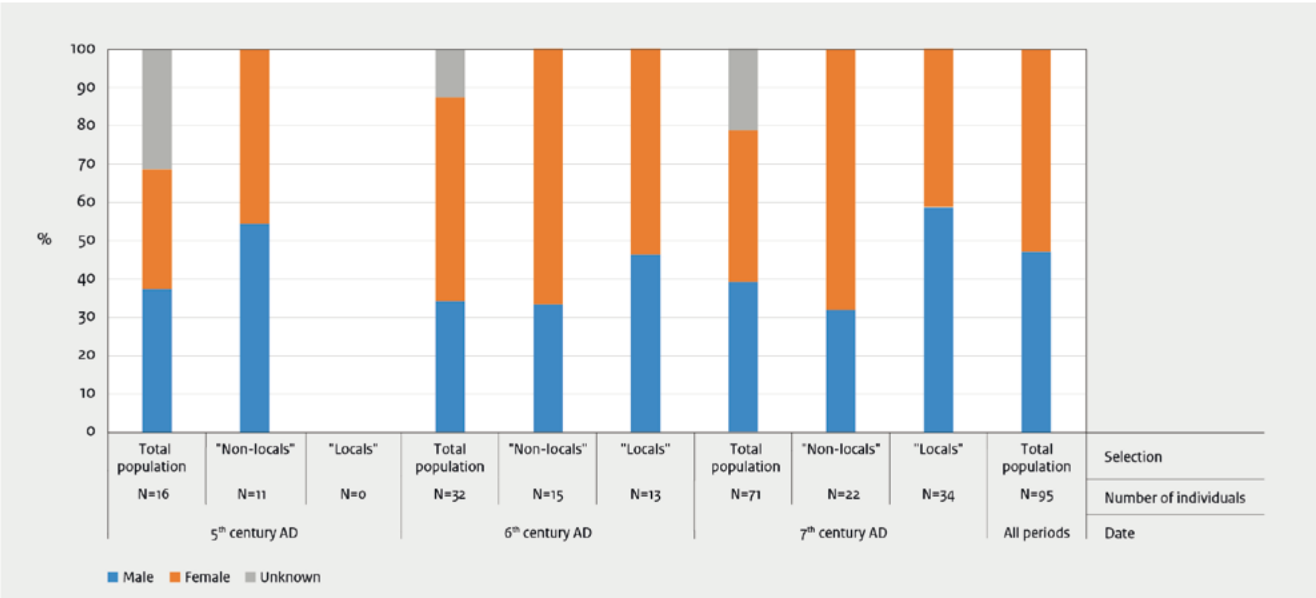

Figure 6.3. Overview of the ratio of identified males and females per time period and per group (those of 'local' and 'non-local' origin). Total number of individuals included in this graph is 119. One individual (Hogebeintum FM109) was excluded due to the absence of a relative or absolute dating.

However, cautiousness is required, due to the low number of non-local individuals per period any claims with enough statistical certainty cannot be supported. However, having said this, it is highly suggestive that 5th-century individuals of non-local descent show a more or less equal division of the sexes, as does the complete dataset, while for the 6th and 7th century, the individuals of non-local origin are dominated by females.

This trend, together with the high number of individuals showing clear evidence for intra-individual mobility observed before, strongly suggests that in the 5th century communities consisting of female and male members and children travelled, while in later centuries, primarily female individuals were mobile. This could fit a model of patrilocal exogamy: communities in the newly colonized areas sustained ties with communities further away for trade as well as marriage partners, and it were the girls or young women that travelled towards the family of their husband-to-be.

7 General conclusion

The combined Sr-O isotope data of 120 individuals dating to roughly the late 4th to 7th century AD has provided a first-ever insight in to palaeomobility patterns in a more quantitative way. More importantly, in the context of this study, the data contribute to answering NOaA research question 58: *What is the nature and background of regional and chronological differentiation in population decline, population growth and population composition? (Key topic 6: Emigration, immigration, acculturation)*. Within this research topic, four sub-questions were defined, which are (partly) answered in this section.

1. To what extent are there individuals among those buried in graves/graveyards from the period 400-700 who did not grow up locally?
The percentage of individuals that exhibit non-local strontium and/or oxygen isotope compositions is 100% in the 5th century AD and then decreases to 53% in the 6th, and finally 34% in the 7th century AD. The number of individuals that show high (>0.0002) intra-individual changes in $^{87}Sr/^{86}Sr$ also decreases towards the 7th century AD: from 94% in the 5th to 47% and 27% in the 6th and 7th century AD respectively. The evidence of migration, specifically in the 5th century AD, but also in the subsequent periods, can contribute to a broader understanding of relationships, trade, and exchange between regions throughout the North Sea area, and with regions further inlands and highlights the important role of human mobility in Early Medieval Europe.

2. What is the (geographical) origin of the non-locals?
This question is to date extremely challenging to answer and will probably remain so for the foreseeable future, due to the strong overlap between strontium isotope ratios and oxygen isotope values in Europe (see also Chapter 4). Only the extremely high or low $^{87}Sr/^{86}Sr$ may be unique enough to identify a region of origin. For most data, the obtained isotope data must be combined with archaeological evidence to further pinpoint the possible regions of origin.

In this study, none of the ratios were extreme to the extent that they could be linked with certainty to a geological region or geographical area. Also, the ratios as low as those from e.g., Oosterbeintum, Oegstgeest, Lent, and Zutphen (all ± 0.7082) occur in different parts of Europe, such as in Great Britain, Germany, and France. In a number of cases (n = 135), however, Great Britain could be excluded as a possible region of origin because the $\delta^{18}O_{PDB}$ values are not compatible with an origin on an island surrounded by water (all data lower than −5.28 ‰ and higher than −3.26 ‰).

3. What is (why) the most plausible explanation for their presence? (group migration versus individual mobility)
Within the non-local individuals dating to the 5th century, a more or less equal division of the sexes is evident. Together with the high intra-individual mobility observed before, this suggests that in the 5th century, communities consisting of female and male members and non-adults travelled. This fits a model of group migration. However, only the composition of groups is now elucidated; the size of those groups cannot be established by isotope analysis.

In contrast to the 5th century, the demographic data for the 6th and 7th century suggests that primarily female individuals were mobile. Moreover, the overall rate of non-local individuals is slightly lower than before. This could fit a model of mobility on a smaller scale, in which exogamy and patrilocal residence were the rule. It seems that communities in newly colonized areas sustained ties with communities further away for trade as well as marriage partners, and it were probably the girls or young women that travelled towards the family of their husband-to-be.

4. Broader context: How do the results compare with those of similar research into demographic aspects of the Roman-Early Medieval transition?
In the above contextualization (Sections 6.2 to 6.4), the isotopic analysis has been set against a background of demographic trends based on settlement and burial archaeology. The evidence fits remarkably well. For the late 3rd/4th century, the archaeological evidence suggests widespread discontinuity or at least dislocation, followed by re-population. The isotope data now confirm high levels of mobility in the 5th century, since all individuals dating to this period show non-local origins and/or intra-individual mobility. For the late 5th/6th century the archaeological sources showed a re-population if that was not evident already in the preceding period, and apparent continuity for those

regions already inhabited. This too is also seen in the isotope data, with a mixed picture of locals/non-local individuals. For the 7th century, the archaeological analysis suggested even higher levels of continuity, which is mirrored by the isotopes with fewer non-local individuals.

7.1 Further research

The current results are a clear expression of the high potential of this type of research. At the same time, it calls for similar research into to later periods (8th century and later). Recent research carried out for the Province of South Holland shows that the $^{87}Sr/^{86}Sr$ of the vast majority of the 10th to 12th-century population from the provinces of North and South Holland is compatible with the expected local signature (0.7088-0.7095). Although mobility within isotopically identical areas is of course not excluded, these data give no indication that large-scale mobility existed in these centuries; despite the fact that the work in the polders probably required additional people. Although the overlap in research areas between this study and the present one is very small, the difference in prevalence in mobility/non-local individual could give a first indication of the end of the human diaspora in post-Roman Europe. Additional research, however, is essential to gain a better understanding of the population dynamics in the 8th century and later periods in the Netherlands.

Moreover, an opportunity for quality improvement of the results is available in the form of aDNA research, which is now sufficiently developed. By employing aDNA analysis on the same individuals, familial relations between sampled individuals could be researched, further investigating the impression from the current research that communities travelled in the 5th century while more individual mobility of females is observed in later periods. This type of research could also better answer the question of origin of the settlers, which is hard to answer by the Sr-O isotopic research conducted here.

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Appendices

Appendix I

Chronology of human deciduous and permanent dentition. Average crown formation times for Western/European populations (data adopted from Nelson & Ash 2010, table adapted from Kootker, 2017).

		FDI notation		Average crown formation times	
Dentition	**Tooth**	**Right quadrant**	**Left quadrant**	**Initiation (Ci)**	**Completion (Crc)**
Deciduous maxillary teeth	Central incisor	51	61	14 weeks i.u.	1.5 mon.
	Lateral incisor	52	62	16 weeks i.u.	2.5 mon.
	Canine	53	63	17 weeks i.u.	9 mon.
	First molar	54	64	15.5 weeks i.u.	6 mon.
	Second molar	55	65	19 weeks i.u.	11 mon.
Deciduous mandibular teeth	Central incisor	81	71	14 weeks i.u.	2.5 mon.
	Lateral incisor	82	72	16 weeks i.u.	3 mon.
	Canine	83	73	17 weeks i.u.	9 mon.
	First molar	84	74	15.5 weeks i.u.	5.5 mon.
	Second molar	85	75	18 weeks i.u.	10 mon.
Permanent maxillary teeth	Central incisor	11	21	3-4 mon.	4-5 yr.
	Lateral incisor	12	22	10-12 mon.	4-5 yr.
	Canine	13	23	4-5 mon.	6-7 yr.
	First premolar	14	24	1.5-1.75 yr.	5-6 yr.
	Second premolar	15	25	2-2.25 yr.	6-7 yr.
	First molar	16	26	Birth	2.5-3 yr.
	Second molar	17	27	2.5-3 yr.	7-8 yr.
	Third molar	18	28	7-9 yr.	12-16 yr.*
Permanent mandibular teeth	Central incisor	41	31	3-4 mon.	4-5 yr.
	Lateral incisor	42	32	3-4 mon.	4-5 yr.
	Canine	43	33	4-5 mon.	6-7 yr.
	First premolar	44	34	1.75-2 yr.	5-6 yr.
	Second premolar	45	35	2.25-2.5 yr.	6-7 yr.
	First molar	46	36	Birth	2.5-3 yr.
	Second molar	47	37	2.5-3 yr.	7-8 yr.
	Third molar	48	38	8-10 yr.	12-16 yr.*

Key: FDI notation: a two-digit system (ISO 3950) developed by the Fédération Dentaire Internationale (FDI) to associate information to a specific tooth. Syntax: <quadrant code><tooth code>. Ci - cusp initiated; Crc - crown completed (developmental stages conform to Moorrees *et al.* 1963); * - formation age extended to 16 due to observed inconsistencies and variations in literature with regards to M3 crown formation times (Liversidge 2008; Nelson & Ash 2010); i.u. - *in utero*; yr. – year.

Appendix II

Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Area	Province	Site	Toponym	¹⁴C code	BP	±	From	To	BC/AD	Sex	
A	Friesland	Harlingen	Midlum	GrA-68001	1500	30	545	600	AD	F*	
A	Friesland	Harlingen	Midlum	GrA-67994	1560	30	430	540	AD	F*	
A	Friesland	Harlingen	Midlum	GrA-67995	1600	30	410	535	AD	F*	
A	Friesland	Harlingen	Midlum	GrA-67997	1480	30	555	615	AD	F*	
A	Friesland	Harlingen	Midlum	GrA-68000	1505	30	540	600	AD	F*	
A	Friesland	Harlingen	Midlum	GrA-68002	1605	30	405	535	AD	F*	
A	Friesland	Hogebeintum	Dorpswierde	Ua-69914	1484	28	551	640	AD		
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69915	1677	29	257	432	AD	F*	
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69917	1614	28	414	539	AD	F	
A	Friesland	Hogebeintum	Dorpswierde	Ua-69918	1570	28	426	562	AD		
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69910	1587	29	419	547	AD	M*	
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69911	1688	28	258	419	AD	M*	
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69912	1287	28	662	774	AD	M*	
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69913	1684	28	332	403	AD	M*	
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Hogebeintum	Dorpswierde	Ua-69916	1588	28	420	546	AD		
A	Friesland	Hogebeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde				550	750	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde				500	600	AD	F	
A	Friesland	Oosterbeintum	Dorpswierde				525	600	AD		
A	Friesland	Oosterbeintum	Dorpswierde	Ua-69996	1535	28	435	599	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde				475	525	AD	F	
A	Friesland	Oosterbeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde	Ua-69997	1575	28	424	557	AD	F	
A	Friesland	Oosterbeintum	Dorpswierde				475	525	AD	–	
A	Friesland	Oosterbeintum	Dorpswierde				450	750	AD	C	
A	Friesland	Oosterbeintum	Dorpswierde				450	550	AD		
A	Friesland	Oosterbeintum	Dorpswierde	Ua-69998	1556	28	430	575	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde				550	725	AD	M	

Dates without a ^{14}C identification number are based on traditional typochronological dating of artefacts. Key: * - aDNA data; ** Sr data previously published, O data generated in this study.

Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Sample ID	Element	^{87}Sr/^{86}Sr	2SE	Analysis by	Reference	δ^{13}C (‰ PDB)	SD	δ^{18}O (‰ PDB)	SD	δ^{18}O (‰ Phospate)
V172–M20–I1	33	0.709591	9	VU/TRITON	Hielkema *et al.* 2017**	−13.27	0.06	−6.02	0.06	
V175–M21–I2	18	0.709880	9	VU/TRITON	Hielkema *et al.* 2017**	−12.75	0.06	−7.44	0.09	
V177–M22–I3	28	0.709277	8	VU/TRITON	Hielkema *et al.* 2017**	−14.61	0.08	−5.85	0.09	
V214–M23–I5	26	0.711403	10	VU/TRITON	Hielkema *et al.* 2017**	−15.50	0.09	−5.19	0.08	
V257–M24–I6	16	0.710482	9	VU/TRITON	Hielkema *et al.* 2017**	−15.60	0.07	−5.27	0.06	
V258–M25–I7	13	0.710152	8	VU/TRITON	Hielkema *et al.* 2017**	−13.49	0.09	−6.22	0.08	
FM100 – kist 249 II	36	0.713396	6	VU/TRITON	This study	−13.10	0.07	−4.28	0.13	
FM100 – kist 249 II	37	0.713417	8	VU/TRITON	This study	−11.94	0.10	−4.02	0.24	
FM101 – 28–360	37	0.711370	12	VU/TRITON	This study	−13.68	0.07	−5.82	0.14	
FM101 – 28–360	46	0.711104	9	VU/TRITON	This study	−14.01	0.08	−4.78	0.15	
FM101 – 28–360	48	0.710635	8	VU/TRITON	This study	−14.25	0.08	−5.45	0.13	
FM107 – kist 251	26	0.710485	4	VU/TRITON	This study	−15.34	0.08	−6.20	0.14	
FM108 – kist 251	37	0.710019	8	VU/TRITON	This study	−14.06	0.08	−6.04	0.09	
FM108 – kist 251	46	0.709848	8	VU/TRITON	This study	−14.79	0.09	−6.06	0.11	
FM109 – kist 251	36	0.709115	9	VU/TRITON	This study	−13.05	0.12	−3.70	0.12	
FM109 – kist 251	47	0.709126	10	VU/TRITON	This study	−12.60	0.09	−4.11	0.21	
FM109 – kist 251	48	0.709091	8	VU/TRITON	This study	−12.98	0.08	−4.36	0.11	
FM95 – kist 249	28	0.709513	8	VU/TRITON	This study	−12.12	0.09	−5.79	0.08	
FM95 – kist 249	36	0.710382	10	VU/TRITON	This study	−14.85	0.06	−4.77	0.08	
FM95 – kist 249	37	0.710669	8	VU/TRITON	This study	−13.93	0.08	−6.15	0.08	
FM96 – kist 249	17	0.710618	8	VU/TRITON	This study	−13.36	0.09	−5.57	0.13	
FM96 – kist 249	26	0.710270	14	VU/TRITON	This study	−14.30	0.08	−5.27	0.08	
FM96 – kist 249	38	0.709540	10	VU/TRITON	This study	−11.88	0.11	−5.60	0.21	
FM98 – kist 249 II	46	0.709288	9	VU/TRITON	This study	−14.30	0.09	−5.39	0.22	
FM98 – kist 249 II	47	0.709129	10	VU/TRITON	This study	−13.78	0.09	−5.31	0.05	
FM98 – kist 249 II	48	0.708928	6	VU/TRITON	This study	−13.43	0.04	−5.80	0.13	
FM99 – kist 249 II	46	0.710224	6	VU/TRITON	This study	−13.73	0.07	−6.53	0.12	
FM99 – kist 249 II	47	0.710896	6	VU/TRITON	This study	−13.95	0.06	−6.32	0.11	
W98 – FM104 – kist 250 II	16	0.709162	7	VU/TRITON	This study	−14.61	0.11	−4.74	0.18	
W98 – FM104 – kist 250 II	17	0.709129	8	VU/TRITON	This study	−14.08	0.10	−5.69	0.18	
S100	35	0.708868	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
S241	25	0.711208	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	18.00
S335	27	0.709232	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.30
S335	36	0.708874	6	VU/TRITON	This study	−9.93	0.18	−5.89	0.16	
S335	48	0.708156	8	VU/TRITON	This study	−12.07	0.07	−5.94	0.15	
S360	17	0.709993	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	16.40
S360	38	0.709627	7	VU/TRITON	This study	−13.35	0.10	−5.21	0.11	
S360	46	0.710021	9	VU/TRITON	This study	−13.71	0.05	−5.34	0.13	
S398	47	0.710330	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.40
S405	25	0.709642	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.60
S410	35	0.708824	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.20
S410	36	0.709133	10	VU/TRITON	This study	−13.03	0.06	−4.00	0.15	
S410	38	0.709110	8	VU/TRITON	This study	−12.19	0.06	−6.63	0.14	
S420	38	0.709404	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.60

Dates without a ^{14}C identification number are based on traditional typochronological dating of artefacts. Key: * - aDNA data; ** Sr data previously published, O data generated in this study.

Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Area	Province	Site	Toponym	^{14}C code	BP	±	From	To	BC/AD	Sex	
A	Friesland	Oosterbeintum	Dorpswierde				675	750	AD	–	
A	Friesland	Oosterbeintum	Dorpswierde	Ua-69999	1554	28	431	577	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde				550	700	AD		
A	Friesland	Oosterbeintum	Dorpswierde				450	750	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde				450	750	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde	Ua-70000	1569	28	427	563	AD	M	
A	Friesland	Oosterbeintum	Dorpswierde				450	650	AD		
A	Friesland	Oosterbeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde				450	750	AD	F?	
A	Friesland	Oosterbeintum	Dorpswierde				450	750	AD	F?	
A	Friesland	Oosterbeintum	Dorpswierde				525	625	AD		
A	Friesland	Oosterbeintum	Dorpswierde								
A	Friesland	Oosterbeintum	Dorpswierde	Ua-70001	1477	27	558	643	AD	F?	
A	Friesland	Oosterbeintum	Dorpswierde	Ua-70002	1571	28	426	561	AD	M?	
A	Friesland	Oosterbeintum	Dorpswierde				440	485	AD		
A	Friesland	Oosterbeintum	Dorpswierde	024707P	1610	15	397	535	AD	F*	
A	Friesland	Oosterbeintum	Dorpswierde				440	485	AD		
A	Friesland	Oosterbeintum	Dorpswierde				625	750	AD	F	
A	Friesland	Oosterbeintum	Dorpswierde	Ua-70004	1561	27	430	569	AD	F?	
A	Friesland	Oosterbeintum	Dorpswierde				525	625	AD		
A	Friesland	Oosterbeintum	Dorpswierde				475	525	AD		
A	Friesland	Oosterbeintum	Dorpswierde	Ua-69995	1611	27	416	538	AD	F	
A	Friesland	Oosterbeintum	Dorpswierde				400	550	AD	M?	
A	Friesland	Oosterbeintum	Dorpswierde				450	650	AD	C	
D	Gelderland	Ewijk	Keizershoeve				400	470	AD	M	
D	Gelderland	Ewijk	Keizershoeve								
D	Gelderland	Ewijk	Keizershoeve				400	470	AD	M	
D	Gelderland	Ewijk	Keizershoeve								
D	Gelderland	Ewijk	Keizershoeve								
D	Gelderland	Lent	Azaleastraat				630	680	AD	F	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat	Ua-69987	1506	22	405	610	AD	F	
D	Gelderland	Lent	Azaleastraat	GrM-19026	1446	21	575	649	AD		
D	Gelderland	Lent	Azaleastraat				630	680	AD	M	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	680	AD	–	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	680	AD	F	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	680	AD	F?	
D	Gelderland	Lent	Azaleastraat				630	680	AD	–	

Dates without a ^{14}C identification number are based on traditional typochronological dating of artefacts. Key: * - aDNA data; ** Sr data previously published, O data generated in this study.

Complete overview of all (14C) dates and Sr-O-C isotope dataset.

	Sample ID	Element	$^{87}Sr/^{86}Sr$	2SE	Analysis by	Reference	$\delta^{13}C$ (‰ PDB)	SD	$\delta^{18}O$ (‰ PDB)	SD	$\delta^{18}O$ (‰ Phospate)
	S433	45	0.709178	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
	S435	36	0.709475	10	VU/TRITON	This study	−11.77	0.09	−4.76	0.24	
	S435	38	0.710360	9	VU/TRITON	This study	−12.23	0.09	−5.19	0.19	
	S435	47	0.709336	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
	S451	45	0.708961	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
	S458	47	0.709026	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
	S460	36	0.714716	10	VU/TRITON	This study	−15.65	0.08	−7.61	0.11	
	S460	37	0.716448	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
	S460	38	0.713206	7	VU/TRITON	This study	−12.84	0.10	−6.60	0.07	
	S473	47	0.708828	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.80
	S474	25	0.709657	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.60
	S483	17	0.711630	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.20
	S483	38	0.711315	8	VU/TRITON	This study	−13.95	0.07	−5.14	0.14	
	S483	46	0.710894	8	VU/TRITON	This study	−14.72	0.06	−4.91	0.11	
	S486 (485A)	26	0.712280	9	VU/TRITON	This study	−12.77	0.05	−5.83	0.20	
	S486 (485A)	44	0.713245	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.40
	S487 (485B)	36	0.709322	8	VU/TRITON	This study	−13.69	0.07	−4.59	0.16	
	S487 (485B)	44	0.712460	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	19.90
	S501	37	0.710651	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	
	S570	26	0.708884	7	VU/TRITON	This study	−13.40	0.07	−4.67	0.14	
	S570	27	0.708791	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.80
	S60	37	0.709822	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.30
	S60	38	0.709387	8	VU/TRITON	This study	−13.58	0.04	−4.51	0.16	
	S605	34	0.709000	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	17.50
	S624	27	0.709077	–	Bradford/TRITON	McManus *et al.* 2013	–	–	–	–	18.40
	V42/INH1	46	0.709979	8	VU/TRITON	Kootker *et al.*, in prep.	−14.07	0.17	−5.61	0.11	
	V42/INH1	47	0.710662	8	VU/TRITON	Kootker *et al.*, in prep.	−13.95	0.07	−5.41	0.08	
	V67/INH2	26	0.711241	9	VU/TRITON	Kootker *et al.*, in prep.	−14.19	0.08	−4.87	0.06	
	V67/INH2	27	0.712264	6	VU/TRITON	Kootker *et al.*, in prep.	−15.96	0.08	−5.41	0.08	
	V67/INH2	28	0.711013	6	VU/TRITON	Kootker *et al.*, in prep.	−14.84	0.06	−5.86	0.09	
	1972/01	16	0.708838	7	VU/TRITON	This study	−13.93	0.04	−6.14	0.06	
	1972/01	17	0.708990	8	VU/TRITON	This study	−13.51	0.07	−6.12	0.12	
	1972/01	28	0.708954	8	VU/TRITON	This study	−13.70	0.06	−6.11	0.06	
	1972/11	47	0.708914	14	VU/TRITON	This study	−12.52	0.11	−5.77	0.19	
	1972/15	18	0.708857	9	VU/TRITON	This study	−13.35	0.05	−5.66	0.08	
	1972/15	36	0.709068	6	VU/TRITON	This study	−14.20	0.08	−5.78	0.07	
	1972/15	47	0.709058	8	VU/TRITON	This study	−14.10	0.07	−5.98	0.14	
	1972/17	26	0.708681	13	VU/TRITON	This study	−14.52	0.11	−5.98	0.15	
	1972/17	27	0.708237	12	VU/TRITON	This study	−13.82	0.09	−5.72	0.11	
	1972/17	85	0.709604	7	VU/TRITON	This study	−14.35	0.06	−4.98	0.11	
	1972/18	16	0.708929	8	VU/TRITON	This study	−14.15	0.05	−5.65	0.07	
	1972/18	17	0.709109	6	VU/TRITON	This study	−13.99	0.04	−7.37	0.16	
	1972/18	18	0.709079	6	VU/TRITON	This study	−13.14	0.07	−6.42	0.16	
	1972/19	26	0.709533	7	VU/TRITON	This study	−14.05	0.06	−6.35	0.09	
	1972/20	46	0.709343	9	VU/TRITON	This study	−14.05	0.10	−6.28	0.15	

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Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Area	Province	Site	Toponym	^{14}C code	BP	±	From	To	BC/AD	Sex	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat	GrM-19027	1522	22	430	602	AD		
D	Gelderland	Lent	Azaleastraat				630	680	AD	M	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat	Ua-69988	1466	28	565	646	AD	M	
D	Gelderland	Lent	Azaleastraat				630	750	AD		
D	Gelderland	Lent	Azaleastraat				630	680	AD	F?	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat	Ua-69989	1250	28	674	876	AD	M	
D	Gelderland	Lent	Azaleastraat	Ua-69990	1337	28	649	772	AD	M	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	680	AD	F	
D	Gelderland	Lent	Azaleastraat	Ua-69991	1497	28	542	640	AD	-	
D	Gelderland	Lent	Azaleastraat				630	750	AD		
D	Gelderland	Lent	Azaleastraat	Ua-69992	1335	28	649	772	AD	F	
D	Gelderland	Lent	Azaleastraat				630	750	AD		
D	Gelderland	Lent	Azaleastraat				630	750	AD	M	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	750	AD	F	
D	Gelderland	Lent	Azaleastraat	Ua-69993	1232	28	684	882	AD	F	
D	Gelderland	Lent	Azaleastraat				63	750	AD		
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	750	AD	M	
D	Gelderland	Lent	Azaleastraat	Ua-69994	1251	28	674	876	AD	M?	
D	Gelderland	Lent	Azaleastraat				630	750	AD		
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat				630	750	AD	M	
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Lent	Azaleastraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat							-	
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat				300	350	AD	-	
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat				300	370	AD	-	
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat							-	
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Nijmegen	Hugo de Grootstraat				300	370	AD	-	
D	Gelderland	Nijmegen	Hugo de Grootstraat								
D	Gelderland	Zoelen	Scharenburg				390	460	AD	F	
D	Gelderland	Zoelen	Scharenburg								

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Complete overview of all (14C) dates and Sr-O-C isotope dataset.

	Sample ID	Element	$^{87}Sr/^{86}Sr$	2SE	Analysis by	Reference	$\delta^{13}C$ (‰ PDB)	SD	$\delta^{18}O$ (‰ PDB)	SD	$\delta^{18}O$ (‰ Phospate)
	1972/20	47	0.709136	8	VU/TRITON	This study	−14.53	0.05	−6.27	0.06	
	1972/24	26	0.709058	10	VU/TRITON	This study	−13.59	0.06	−4.96	0.08	
	1972/24	27	0.708977	10	VU/TRITON	This study	−13.69	0.03	−5.84	0.22	
	1972/24	28	0.709387	8	VU/TRITON	This study	−14.25	0.09	−6.36	0.11	
	1975/04	36	0.710318	7	VU/TRITON	This study	−14.17	0.09	−4.63	0.08	
	1975/04	37	0.709835	8	VU/TRITON	This study	−13.64	0.08	−4.94	0.11	
	1975/19	16	0.708924	10	VU/TRITON	This study	−15.27	0.06	−6.19	0.08	
	1975/19	75	0.709068	8	VU/TRITON	This study	−14.49	0.06	−5.66	0.10	
	1975/21	48	0.712291	7	VU/TRITON	This study	−13.40	0.05	−6.49	0.14	
	1975/25	PM	0.709197	7	VU/TRITON	This study	−13.27	0.11	−5.85	0.07	
	1975/28	45	0.712090	6	VU/TRITON	This study	−12.63	0.06	−4.89	0.10	
	1975/28	46	0.709272	7	VU/TRITON	This study	−12.29	0.07	−5.14	0.14	
	1975/47	36	0.708972	8	VU/TRITON	This study	−14.95	0.10	−6.90	0.07	
	1975/47	72	0.709037	8	VU/TRITON	This study	−13.94	0.08	−4.40	0.07	
	1975/58	45	0.709726	8	VU/TRITON	This study	−13.53	0.06	−5.87	0.08	
	1975/58	48	0.709744	9	VU/TRITON	This study	−13.66	0.08	−5.73	0.14	
	1975/64	46	0.710901	10	VU/TRITON	This study	−14.76	0.08	−5.34	0.14	
	1975/64	47	0.710169	7	VU/TRITON	This study	−13.22	0.11	−6.35	0.12	
	1975/64	48	0.709755	13	VU/TRITON	This study	−13.04	0.07	−5.00	0.09	
	1975/72	47	0.709021	8	VU/TRITON	This study	−13.64	0.06	−3.92	0.07	
	1975/75	46	0.710320	10	VU/TRITON	This study	−13.33	0.07	−5.47	0.08	
	1975/75	47	0.710002	9	VU/TRITON	This study	−12.75	0.16	−5.98	0.22	
	1975/75	48	0.710312	10	VU/TRITON	This study	−12.56	0.05	−6.10	0.17	
	1975/82	35	0.710865	11	VU/TRITON	This study	−12.74	0.09	−7.35	0.19	
	1975/83	16	0.709290	9	VU/TRITON	This study	−13.78	0.19	−8.04	0.22	
	1975/83	37	0.709884	6	VU/TRITON	This study	−13.03	0.07	−6.12	0.09	
	1975/83	38	0.709828	8	VU/TRITON	This study	−12.82	0.10	−6.62	0.10	
	1975/94	46	0.709168	8	VU/TRITON	This study	−11.60	0.07	−6.24	0.15	
	1975/94	47	0.709209	6	VU/TRITON	This study	−11.85	0.08	−8.41	0.25	
	1975/94	48	0.709100	5	VU/TRITON	This study	−11.09	0.11	−8.74	0.17	
	OO16	36	0.710753	8	VU/TRITON	This study	−12.41	0.07	−7.27	0.10	
	OO16	37	0.710276	8	VU/TRITON	This study	–	–	–	–	
	OO20	16	0.708796	9	VU/TRITON	This study	−12.75	0.07	−4.09	0.09	
	OO20	17	0.708480	9	VU/TRITON	This study	−12.29	0.04	−4.16	0.11	
	OO20	18	0.708596	8	VU/TRITON	This study	−12.20	0.08	−5.16	0.05	
	OO26	36	0.710535	8	VU/TRITON	This study	−13.63	0.04	−5.54	0.10	
	OO26	37	0.710338	6	VU/TRITON	This study	−13.85	0.04	−5.21	0.09	
	OO26	38	0.709972	7	VU/TRITON	This study	−13.58	0.04	−6.33	0.07	
	OO57	46	0.709789	8	VU/TRITON	This study	−11.93	0.08	−4.47	0.17	
	OO57	47	0.710720	9	VU/TRITON	This study	−12.29	0.06	−5.40	0.06	
	OO57	48	0.709502	8	VU/TRITON	This study	−12.07	0.11	−5.38	0.22	
	OO77	16	0.709387	8	VU/TRITON	This study	−11.77	0.15	−6.44	0.19	
	OO77	17	0.709766	8	VU/TRITON	This study	−12.17	0.04	−6.23	0.10	
	V1251/INH3	36	0.711150	8	VU/TRITON	This study	−12.48	0.04	−6.42	0.09	
	V1251/INH3	37	0.711379	6	VU/TRITON	This study	−12.39	0.06	−6.36	0.06	

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Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Area	Province	Site	Toponym	^{14}C code	BP	±	From	To	BC/AD	Sex	
D	Gelderland	Zoelen	Scharenburg								
F	Limburg	Borgharen	Daalderveld-Pasestraat	Beta-321062	1660	30	260	430	AD	M?	
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat	Beta-321065	1550	30	430	580	AD	-	
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat	Beta-321064	1600	30	400	540	AD	F	
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat	Beta-321068	1670	30	260	430	AD	F	
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat	Beta-321070	1570	30	420	560	AD	F	
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat				400	600	AD	M	
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Daalderveld-Pasestraat								
F	Limburg	Borgharen	Pasestraat 1995				550	625	AD	F	
F	Limburg	Borgharen	Pasestraat 1995				550	625	AD	F	
F	Limburg	Borgharen	Pasestraat 1995								
F	Limburg	Borgharen	Pasestraat 1999				550	625	AD	M	
F	Limburg	Borgharen	Pasestraat 1999								
F	Limburg	Borgharen	Pasestraat 1999				550	625	AD	M (Bobo)	
F	Limburg	Borgharen	Pasestraat 2008				550	625	AD	F*	
F	Limburg	Borgharen	Pasestraat 2008				600	700	AD	M*	
F	Limburg	Borgharen	Pasestraat 2008								
F	Limburg	Borgharen	Pasestraat 2009				600	700	AD	M* (C)	
F	Limburg	Borgharen	Pasestraat 2009				600	700	AD	M*	
F	Limburg	Borgharen	Pasestraat 2009				600	700	AD	M*	
F	Limburg	Borgharen	Pasestraat 2009				600	700	AD	F*	
F	Limburg	Borgharen	Pasestraat 2009				625	700	AD	M*	
F	Limburg	Borgharen	Pasestraat 2009								
F	Limburg	Borgharen	Pasestraat 2012	GrA - 55327	1510	30	437	618	AD	F*	
F	Limburg	Borgharen	Pasestraat 2012	GrA-55328	1495	30	470	641	AD	M*	
B	Overijssel	Zutphen	Leesten de Enk (Gerward)								
B	Overijssel	Zutphen	Leesten de Enk (Gerward)								
B	Overijssel	Zutphen	Leesten de Enk (Gerward)				400	400	AD	M	
D	Utrecht	Bunnik	Het Burgje				390	600	AD	F	
D	Utrecht	Bunnik	Het Burgje								
D	Utrecht	Bunnik	Het Burgje								
D	Utrecht	Bunnik	Het Burgje								
D	Utrecht	Bunnik	Het Burgje				450	600	AD	F*	
D	Utrecht	Bunnik	Het Burgje								

Dates without a ^{14}C identification number are based on traditional typochronological dating of artefacts. Key: * - aDNA data; ** Sr data previously published, O data generated in this study.

Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Sample ID	Element	$^{87}Sr/^{86}Sr$	2SE	Analysis by	Reference	δ^{13}C (‰ PDB)	SD	δ^{18}O (‰ PDB)	SD	δ^{18}O (‰ Phospate)
V1251/INH3	38	0.712670	8	VU/TRITON	This study	−12.24	0.05	−6.25	0.10	
S1066	36	0.708210	9	VU/262	Kootker, 2013**	−13.34	0.05	−5.78	0.12	
S1066	47	0.708580	9	VU/TRITON	This study	−11.90	0.07	−5.57	0.14	
S284.1	18	0.709541	13	VU/TRITON	This study	−13.79	0.02	−3.73	0.14	
S284.1	46	0.709707	9	VU/262	Kootker, 2013**	−14.05	0.06	−4.54	0.07	
S284.1	47	0.709353	6	VU/TRITON	This study	−13.17	0.04	−5.27	0.14	
S372	46	0.708989	10	VU/262	Kootker, 2013**	−12.91	0.06	−3.90	0.05	
S372	47	0.709245	7	VU/TRITON	This study	−12.02	0.06	−4.40	0.15	
S372	48	0.709678	7	VU/TRITON	This study	−11.13	0.09	−5.67	0.15	
S747	36	0.711520	9	VU/262	Kootker, 2013	−16.90	0.10	−4.32	0.13	
S747	47	0.710303	6	VU/TRITON	This study	−12.57	0.06	−7.87	0.09	
S747	48	0.710733	8	VU/TRITON	This study	−13.58	0.05	−5.88	0.05	
S822	26	0.712087	8	VU/262	Kootker, 2013	−14.68	0.06	−4.75	0.12	
S822	28	0.708408	10	VU/TRITON	This study	−11.02	0.08	−5.61	0.14	
S822	37	0.710415	10	VU/TRITON	This study	−12.71	0.08	−6.47	0.08	
S851	17	0.709961	8	VU/TRITON	This study	−12.77	0.07	−5.99	0.14	
S851	46	0.709769	9	VU/262	Kootker, 2013**	−13.75	0.03	−4.79	0.08	
S851	1/2.8	0.709598	6	VU/TRITON	This study	−12.67	0.03	−5.39	0.07	
GI	44	0.710478	8	VU/TRITON	This study	−13.43	0.06	−8.56	0.12	
GIV	27	0.708589	8	VU/TRITON	This study	−12.46	0.09	−6.53	0.27	
GIV	28	0.710849	7	VU/TRITON	This study	−12.31	0.08	−6.33	0.09	
GIX	26	0.710051	9	VU/TRITON	This study	−13.15	0.11	−4.89	0.13	
GIX	37	0.710005	7	VU/TRITON	This study	−12.79	0.07	−5.87	0.10	
GVII	36	0.710050	6	VU/TRITON	This study	−12.86	0.11	−5.87	0.19	
V348 / IND14 /2008–2 (S2)	21	0.710359	10	VU/262	Kootker, 2014**	−14.63	0.05	−4.33	0.11	
V746–A – IND15 (S6)	36	0.709928	9	VU/262	Kootker, 2014**	−14.10	0.10	−5.75	0.10	
V746–A – IND15 (S6)	37	0.710106	9	VU/TRITON	This study	−12.90	0.07	−5.36	0.13	
V1104 / IND22 (S51)	41	0.710146	10	VU/262	Kootker, 2014**	−14.29	0.04	−4.72	0.04	
V542 / IND19	83	0.710716	9	VU/262	Kootker, 2014	–	–	–	–	
V701 / IND20 (S46)	I	0.710131	9	VU/262	Kootker, 2014**	−14.43	0.07	−5.10	0.11	
V715 / IND17	33	0.710515	7	VU/262	Kootker, 2014	–	–	–	–	
V785 / IND18 (S15)	36	0.710506	8	VU/TRITON	This study	−13.57	0.07	−5.70	0.16	
V785 / IND18 (S15)	54	0.710595	7	VU/262	Kootker, 2014	–	–	–	–	
V1244 / IND21 (S47)	36	0.710396	10	VU/262	Kootker, 2014	–	–	–	–	
V1794 / IND23 (S7)	24/25	0.710050	6	VU/262	Kootker, 2014**	−14.18	0.05	−5.69	0.05	
1331	36	0.708297	7	VU/TRITON	This study	−11.90	0.09	−3.58	0.11	
1331	47	0.708170	7	VU/TRITON	This study	−12.21	0.13	−4.67	0.39	
1331	48	0.708204	8	VU/TRITON	This study	−12.84	0.17	−5.44	0.10	
V137/INH5	16	0.711122	10	VU/TRITON	Kootker *et al.*, in prep.	−14.30	0.08	−4.35	0.09	
V137/INH5	37	0.711608	8	VU/TRITON	Kootker *et al.*, in prep.	−13.99	0.07	−5.10	0.09	
V137/INH5	48	0.711912	7	VU/TRITON	Kootker *et al.*, in prep.	−14.09	0.05	−5.54	0.09	
V192/INH6	38	0.709083	7	VU/TRITON	Kootker *et al.*, in prep.	−14.25	0.08	−4.97	0.05	
V192/INH6	46	0.709130	7	VU/TRITON	Kootker *et al.*, in prep.	−14.05	0.07	−4.65	0.07	
V192/INH6	47	0.709106	8	VU/TRITON	Kootker *et al.*, in prep.	−13.83	0.06	−5.02	0.09	

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Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Area	Province	Site	Toponym	^{14}C code	BP	±	From	To	BC/AD	Sex	
D	Utrecht	Bunnik	Het Burgje				450	600	AD	M*	
D	Utrecht	Bunnik	Het Burgje								
D	Utrecht	Bunnik	Het Burgje								
B	Utrecht	Elst	't Woud				510	565	AD	M	
B	Utrecht	Elst	't Woud								
B	Utrecht	Elst	't Woud								
B	Utrecht	Elst	't Woud				510	565	AD	M	
B	Utrecht	Elst	't Woud								
B	Utrecht	Elst	't Woud								
B	Utrecht	Elst	't Woud				500	700	AD	F	
B	Utrecht	Elst	't Woud				540	590	AD	F	
B	Utrecht	Elst	't Woud				540	590	AD	M	
B	Utrecht	Elst	't Woud								
D	Utrecht	Houten	Hoogdijk	Ua-69927	1417	27	599	658	AD	-	
D	Utrecht	Houten	Hoogdijk								
D	Utrecht	Houten	Hoogdijk								
B	Utrecht	Leusden	Oud Leusden 1984				550	710	AD	-	
B	Utrecht	Leusden	Oud Leusden 1984								
B	Utrecht	Leusden	Oud Leusden 1984								
D	Utrecht	Wijk bij Duurstede	Veilingterrein	SUERC-35889	1310	30	650	780	AD	F	
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein				-	-		M	
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein	KIA-32736	1395	24	605	673	AD	F	
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein	SUERC-35888	1335	30	640	730	AD	F	
D	Utrecht	Wijk bij Duurstede	Veilingterrein	Ua-38024	1266	35	660	870	AD	F	
D	Utrecht	Wijk bij Duurstede	Veilingterrein	Ua-38025	1322	33	650	780	AD	F	
D	Utrecht	Wijk bij Duurstede	Veilingterrein	Ua-38026	1371	34	600	700	AD	M?	
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein	SUERC-34857	1390	30	600	675	AD	M	
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
D	Utrecht	Wijk bij Duurstede	Veilingterrein								
C	Zuid-Holland	Leiden	Kop van Leeuwenhoek				500	700	AD	M	
C	Zuid-Holland	Leiden	Kop van Leeuwenhoek								
C	Zuid-Holland	Leiden	Kop van Leeuwenhoek				500	700	AD	M	
C	Zuid-Holland	Leiden	Kop van Leeuwenhoek								
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza				600	700	AD	F*	
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza								

Dates without a ^{14}C identification number are based on traditional typochronological dating of artefacts. Key: * - aDNA data; ** Sr data previously published, O data generated in this study.

Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

	Sample ID	Element	$^{87}Sr/^{86}Sr$	2SE	Analysis by	Reference	$\delta^{13}C$ (‰ PDB)	SD	$\delta^{18}O$ (‰ PDB)	SD	$\delta^{18}O$ (‰ Phospate)
	V228/INH7	46	0.711850	9	VU/TRITON	Kootker *et al.*, in prep.	−13.97	0.08	−4.42	0.09	
	V228/INH7	47	0.710770	8	VU/TRITON	Kootker *et al.*, in prep.	−13.22	0.07	−4.94	0.09	
	V228/INH7	48	0.709690	7	VU/TRITON	Kootker *et al.*, in prep.	−12.79	0.06	−5.37	0.09	
	G174	M1	0.711282	9	VU/TRITON	This study	−15.51	0.04	−5.36	0.15	
	G174	M2	0.710756	8	VU/TRITON	This study	−13.97	0.11	−6.03	0.12	
	G174	M3	0.710610	8	VU/TRITON	This study	−13.41	0.10	−5.78	0.12	
	G178	M1	0.709975	6	VU/TRITON	This study	−15.19	0.08	−5.02	0.10	
	G178	M2	0.710172	8	VU/TRITON	This study	−13.78	0.12	−4.60	0.17	
	G178	M3	0.710481	8	VU/TRITON	This study	−15.10	0.05	−5.54	0.05	
	G210	M1/2	0.710369	6	VU/TRITON	This study	−14.53	0.05	−5.07	0.07	
	G238	M	0.712264	9	VU/TRITON	This study	−12.00	0.10	−4.77	0.23	
	G240	M	0.710509	9	VU/TRITON	This study	−13.07	0.07	−5.14	0.23	
	G240	M3	0.709303	10	VU/TRITON	This study	−12.08	0.07	−4.79	0.10	
	Skelet	36	0.709036	12	VU/TRITON	This study	−14.40	0.07	−4.73	0.08	
	Skelet	37	0.708948	9	VU/TRITON	This study	−13.59	0.11	−5.85	0.16	
	Skelet	38	0.708794	9	VU/TRITON	This study	−13.04	0.07	−5.24	0.15	
	G73–2–2	M1	0.711968	8	VU/TRITON	This study	−13.50	0.06	−5.35	0.09	
	G73–2–2	M2	0.711671	8	VU/TRITON	This study	−13.32	0.12	−5.03	0.19	
	G73–2–2	M3	0.711368	8	VU/TRITON	This study	−12.82	0.08	−5.55	0.31	
	1673–G1–IND4	46	0.709118	8	VU/TRITON	This study	−12.31	0.10	−6.01	0.10	
	1673–G1–IND4	47	0.709281	6	VU/TRITON	This study	−13.47	0.05	−6.11	0.10	
	1673–G1–IND4	48	0.709937	8	VU/TRITON	This study	−13.74	0.10	−5.92	0.14	
	5034–IND10	36	0.709167	6	VU/TRITON	This study	–	–	–	–	
	5034–IND10	37	0.709208	10	VU/TRITON	This study	−13.66	0.07	−6.18	0.07	
	5034–IND10	38	0.709285	10	VU/TRITON	This study	−13.65	0.05	−6.53	0.13	
	536–G8–IND1	36	0.710962	6	VU/TRITON	This study	−11.33	0.10	−6.24	0.24	
	536–G8–IND1	37	0.711214	10	VU/TRITON	This study	−12.50	0.06	−6.45	0.09	
	536–G8–IND1	48	0.709234	8	VU/TRITON	This study	−12.74	0.06	−8.12	0.13	
	5376–G6–IND5	22	0.711932	10	VU/TRITON	This study	−13.94	0.08	−6.38	0.17	
	5595–G3–IND8	27	0.709399	7	VU/TRITON	This study	−14.73	0.06	−5.38	0.07	
	5616–G4–IND6	27?	0.709203	8	VU/TRITON	This study	−13.81	0.06	−5.37	0.20	
	5766–G7–IND9	36	0.708869	10	VU/TRITON	This study	−14.37	0.16	−6.16	0.17	
	5766–G7–IND9	37	0.709161	10	VU/TRITON	This study	−14.37	0.16	−6.16	0.17	
	5766–G7–IND9	38	0.708877	8	VU/TRITON	This study	−13.69	0.09	−6.33	0.14	
	5788–G5–IND7	46	0.709268	7	VU/TRITON	This study	−13.43	0.06	−5.27	0.07	
	5788–G5–IND7	47	0.709671	7	VU/TRITON	This study	−12.50	0.06	−5.77	0.13	
	5788–G5–IND7	48	0.709147	7	VU/TRITON	This study	−13.40	0.15	−5.91	0.08	
	KOL1768/Graf 1/V270	26	0.709412	7	VU/TRITON	This study	−14.48	0.07	−4.75	0.08	
	KOL1768/Graf 1/V270	47	0.709125	8	VU/TRITON	This study	−14.56	0.07	−5.42	0.11	
	KOL18/Graf 2	36	0.709106	8	VU/TRITON	This study	−13.32	0.08	−6.29	0.11	
	KOL18/Graf 2	37	0.709050	9	VU/TRITON	This study	−13.58	0.06	−6.24	0.13	
	S1/V2415/2012–01	16	0.710402	10	VU/262	Van Spelde *et al.*, 2021**	−15.35	0.05	−6.45	0.05	
	S1/V2415/2012–01	38	0.708935	6	VU/TRITON	This study	−14.28	0.07	−5.11	0.10	

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Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

Area	Province	Site	Toponym	^{14}C code	BP	±	From	To	BC/AD	Sex	
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza								
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza				600	700	AD	F*	
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza								
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza								
C	Zuid-Holland	Oegstgeest	Nieuw Rhijngeest-Zuid – SL Plaza				600	700	AD	M*	
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	-	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	V	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	-	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	C	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	M?	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	-	
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	V	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	F	
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn								
C	Zuid-Holland	Rijnsbrug	De Horn				500	700	AD	C	

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Complete overview of all (^{14}C) dates and Sr-O-C isotope dataset.

	Sample ID	Element	$^{87}Sr/^{86}Sr$	2SE	Analysis by	Reference	δ^{13}C (‰ PDB)	SD	δ^{18}O (‰ PDB)	SD	δ^{18}O (‰ Phospate)
	S1/V2415/2012–01	47	0.710229	9	VU/TRITON	This study	−14.21	0.11	−5.82	0.09	
	S24/V2285/2012–02	27	0.709023	11	VU/TRITON	This study	−14.39	0.08	−7.56	0.24	
	S24/V2285/2012–02	28	0.709518	9	VU/TRITON	This study	−14.80	0.06	−6.38	0.10	
	S24/V2285/2012–02	46	0.709318	10	VU/262	Van Spelde *et al.*, 2021**	−15.11	0.05	−5.55	0.06	
	S8/2011–01	73	0.708018	9	VU/262	Van Spelde *et al.*, 2021	−13.24	0.09	−3.11	0.15	
	1913	36	0.709134	12	VU/TRITON	This study	−12.75	0.10	−5.67	0.28	
	1913	37	0.708749	6	VU/TRITON	This study	−14.06	0.06	−5.64	0.10	
	E3.2+E4.2	37	0.708675	7	VU/TRITON	This study	−13.40	0.07	−4.42	0.21	
	E3.2+E4.2	46	0.708761	6	VU/TRITON	This study	−13.30	0.08	−4.41	0.19	
	E3.2+E4.2	..8	0.708983	7	VU/TRITON	This study	−11.93	0.06	−4.59	0.18	
	h1913/4.101	16	0.709374	7	VU/TRITON	This study	−14.32	0.12	−5.67	0.15	
	h1913/4.101	17	0.709283	13	VU/TRITON	This study	−13.75	0.05	−6.16	0.15	
	Lijk 2 – 2.1 – kind	16	0.709189	14	VU/TRITON	This study	−13.70	0.06	−5.81	0.05	
	Lijk 2 – 2.1 – kind	17	0.709033	10	VU/TRITON	This study	−13.12	0.08	−7.45	0.15	
	Lijk 2 – 2.2 – Volwassene 1	46	0.709133	8	VU/TRITON	This study	−13.44	0.11	−6.88	0.14	
	Lijk 2 – 2.2 – Volwassene 1	47	0.709117	10	VU/TRITON	This study	−13.83	0.09	−6.32	0.14	
	Lijk 2 – 2.3 – Volwassene 2	3/46	0.709428	10	VU/TRITON	This study	−14.12	0.13	−5.15	0.19	
	Lijk 5	36	0.708417	9	VU/TRITON	This study	−15.19	0.16	−6.78	0.15	
	Lijk 5	37	0.708963	12	VU/TRITON	This study	−12.59	0.09	−5.63	0.30	
	Lijk 5	38	0.709222	8	VU/TRITON	This study	−14.45	0.12	−7.00	0.15	
	Lijk 6 (3, 12 Dijkstra)	36	0.709987	8	VU/TRITON	This study	−12.73	0.07	−5.99	0.24	
	Lijk 6 (3, 12 Dijkstra)	37	0.710010	9	VU/TRITON	This study	−12.48	0.08	−6.29	0.08	
	Lijk 6 (3, 12 Dijkstra)	38	0.710014	8	VU/TRITON	This study	−11.21	0.08	−6.31	0.22	
	No.14 IND E5	M1	0.709037	7	VU/TRITON	This study	−12.74	0.09	−6.22	0.18	

Dates without a ^{14}C identification number are based on traditional typochronological dating of artefacts. Key: * - aDNA data; ** Sr data previously published, O data generated in this study.

This publication presents the results of an extensive strontium (Sr) and oxygen (O) isotope study of 120 late Roman and early medieval individuals from the Netherlands dating from the late 4th to the 7th century AD. The presence of post-Roman human immigration had already been demonstrated by settlement and burial archaeology; however, direct biological evidence of the human individuals was lacking. This report provides a first and essential quantitative insight into the role that palaeomobility played in the post-Roman Netherlands. Advancing insights within isotope archaeology and the cultural archaeological field may lead to different interpretations than presented in this report. Therefore, this study should be seen primarily as a first step in the qualification of mobility in Early Medieval Netherlands and as a basis for further synthesising research.

This scientific report is intended for archaeologists, as well as for other professionals and amateur enthusiasts involved in archaeology.

The Cultural Heritage Agency provides knowledge and advice to give the future a past.