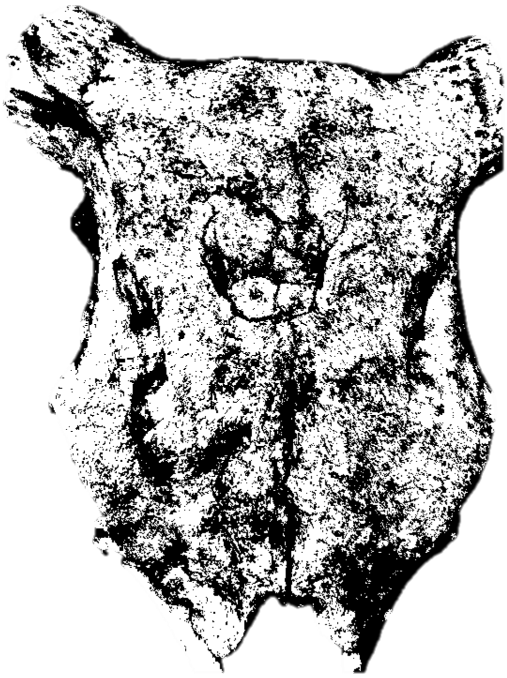
Beyond the Harbour

Tracing animal mobility in the context of an urban Viking Age town, utilising a multi-isotopic approach.



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Frontpage illustration: cow skull from the 2015/2016 Harbour excavations at Birka.
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Abstract

Prehistoric urban towns have been debated within many fields and sub disciplines, throughout the years. Archaeological material has cast light on far reaching contacts of urban places and their trading networks. The towns that developed during the Viking Age have long been debated in light of urban definitions, and how these places connected to the wider world. Consequently, physically tracing these networks in utilising archaeological material alone has been both restrictive and beneficial. Consequently, to understand these prehistoric socioeconomic networks better, one aspect of it was chosen for this study: animal economy. Central place theory and World System theory serves as good proxies for conceptualising the socioeconomic networks of the Viking Age, and other contemporary places with similar developments. The Viking Age was a time with both political and socioeconomic turmoil, ending with a change in the way people lived, and what they believed in. Isotope analysis had been utilised for the past four decades to trace mobility, diet and migrations in both humans and animals. A multi-isotopic approach utilising carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), sulphur ($\delta^{34}S$), strontium ($^{87/86}Sr$) and radiocarbon dating (^{14}C) from animal bone and teeth were conducted for this thesis. The results were indicative of a vast reaching network for import of animals for the animal economy and the food provisioning of the Viking Age town of Birka. The results are interpreted as reflecting different values for the taxonomic groups deriving from different places based on different dietary niches. This type of research proves valuable to understand and connect the prehistoric world of the Viking Age and their urban towns to the interdependence between town and hinterland, and beyond.

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Abbreviations and Definitions

NCS = Nitrogen Carbon Sulphur

Sr = Strontium

C = Carbon

S =Sulphur

N = Nitrogen

s.d/± = standard deviation

L = Layers

PQ = Squares

BP = Before Present

CE = Common Era

BdP= Bead Period

Isoscape = geological map/overview of isotope values and their distribution in the landscape

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Chapter 1. Introduction

1.1 Introduction:

The Viking Age in Scandinavia is considered the period between 793-1050 Common Era (CE) (Lund and Sindbæk 2021:1-5). This is the period that historically comes after the Migration Period 300-700 CE in which as suggested by the name itself, assortments of people migrated in the search for more fertile land and better living conditions (Barrett 2008; Gundersen 2019). One of the reasons for this migration event is thought to be due to a dust veil caused by a volcanic eruption that occurred around 536 CE and lasted for several decades, causing the living conditions in Europe to be less than favourable due to insufficient cultivation conditions (Gundersen 2019). This amongst other theories such as escalation of developing maritime technologies, movement of people, economic advantages, climate change and marriage alliances, whichever one choses to rely on, this stages the backdrop from which the Viking Age emerges (Barrett 2008; Lund and Sindbæk 2021:4).

The Viking Age is perceived as a violent time with people from Scandinavia attacking, pillaging, undertaking dangerous voyages and leaving behind a trail of destruction (Barrett 2008:671; Ambrosiani 2013:13). The attack on Lindisfarne in 793 CE is historically the starting point of the Viking Age (Brink and Price 2008:5; Lund and Sindbæk 2021:5). This backdrop sets the stage for change occurring during this time, with its economic and socio-political turmoil (Amorosi et al. 1997; Holt 2007; Sindbæk 2007a; Jones and Mulville 2018; Croix et al. 2020:3). However, for the most part people of the Viking Age were farmers, with focus on family and subsistence removed from violence of the time (Kalmring and Holmquist 2015). The Viking Age were also a time of growth of networks, economy, stock farming and developing technologies. During the Viking Age, places of a different character than before developed. These places have been described as nodes of trade, central places of commerce and alliances (Ericson et al. 1988; Callmer 1994:64). These places have often been connected to trade and international people, however, the question of their subsistence and where it derived from has been left relatively open.

Within the field of archaeology the investigation of past mobility, network and development of towns and cities has always been a central part of the quest to understand prehistory. In the past these topics has been investigated through historical sources, linguistics, and material culture (Burmeister 2000; LaViolette and Fleisher 2005; Lund and Sindbæk 2021). However, these categories can only give us some answers to our lingering questions about the prehistoric past, and how socioeconomic networks, places and mobility were connected (Helle 1994; Kintigh et al. 2014). There is a general debate within the field of archaeology on what can be defined as an urban town in prehistory, and it is referred to here as the urban debate. Consequently, this ties in with some of the grand challenges in archaeology, especially the question of how places developed, sustained and decline in prehistory (Kintigh et al. 2014; Carballo and Fortenberry 2015; Holmquist et al. 2016; Croix et al. 2020; Lund and Sindbæk 2021).

Gaastra et al. (2020) said that one of the main economic foundations in the development of surplus is said to be the production of livestock and is in essence the building block for any emergence of complex societies, including urban towns (Arnold et al. 2018:1-2; Gaastra et al. 2020). To better understand how places came to be and flourish it is important to start with the basic of human needs, sustenance. Where did prehistoric places get their food from and how did they utilise the landscape and networks to obtain it? Hence, the focal point of this thesis is animal mobility, and how that can interlink with the socioeconomic networks of urban towns which will also be referred to throughout this thesis as central places.

Animal mobility is dependent on organisation, without a certain level of organisation safely ensuring the subsistence needs of a place the place would be at risk. Historically some animals have been utilised for private or less commoditised purposes, like sheep and pig since they take up little space for private homes and other commercial activities (Zeder 1988; Zeder 1998; Wigh 2001; Skre 2012). When considering animal economy, two models are of relevance: indirect provisioning and direct provisioning. Direct provisioning is when animals are delivered directly to the consumer, indirect is when several components are involved and there is an overall control of the animals as a commodity (Zeder 1988; Arnold et al. 2018). Some fundamental aspects for an economy to develop in an indirect provisioning system is the need for storage of the good, ergo meat, and to free people of subsistence tasks. The further away the commodity derives from, the more organisation it will take for it to be delivered in suitable condition, and through perhaps several directories (Zeder 1988:11). Hence larger animals like cattle would take a great deal of organisation to distribute. Therefore cattle would often be a walking commodity meaning transported alive to its destination, as this makes the pragmatic aspects of the mobility easier (Zeder 1988:11; Wigh 2001:137). When the need for production of things outweighs the need for subsistence a social stratification can be deduced, social stratification is also said to be one of the key components of an urban development (Zeder 1988:9-12; Arnold et al. 2018:7,8).

Isotopic analysis is a scientific technique which has revolutionised the field of archaeology over the past four decades and brought archaeological science to new levels of application. Isotope analysis can be used to elucidate and understand past diet, mobility and environment (Sayle et al. 2013; Wright 2017b; Roberts et al. 2018; Sayle et al. 2019). In this regard, isotopic analysis can give us a deeper understanding of questions linked to mobility, diet, environmental and socioeconomical aspects in prehistory (Fernandes and Jaouen 2017). Consequently, this technique can be utilised as a valuable research tool in addition to archaeological theory. This thesis will hence employ a multi-isotopic approach utilising sulphur ($\delta^{34}S$), nitrogen ($\delta^{15}N$), carbon ($\delta^{13}C$), strontium ($^{87/86}Sr$) values and radiocarbon dating (^{14}C) to investigate animal mobility in the context of an urban Viking Age town. Further, engaging in an interdisciplinary discussion of socioeconomic networks. By doing so, this isotopic study will shed some light as to the extent of the networks that were forged to sustain the central places that developed during the Viking Age and beyond (Sayle et al. 2013; Price et al. 2018; Hamilton et al. 2019).

1.2 Problem statement:

The aim is to investigate socioeconomic networks of central places using animal mobility as a proxy in an urban Viking Age context and to further explore the connections to the hinterland and beyond it. Central places in prehistory have often been associated with a maritime character, and urban traits (Kalmring and Holmquist 2015; Kusimba and Walz 2018; Lund and Sindbæk 2021). This current exploration of central places will step beyond the harbour, which was the focal point of the 2015/2016 Harbour excavation at Birka. By investigating a single fundamental aspect of urban society namely animal economy, in doing so it will shed light on the networks which connected this prehistoric world. The sustenance of the Viking Age town of Birka will be investigated through a multi-isotopic approach, utilising 45 samples from the domesticated animals: cattle (*Bos taurus*), pig (*Sus scrofa*) and sheep (*Ovis aries*). Birka will be referred to as a Viking Age site since it is during this time most of the research of the place attests to however, throughout this thesis some earlier dates will be mentioned on the basis of ^{14}C dates.

The following research questions will be investigated throughout this thesis:

- **How can isotope analysis of animal bones and teeth from the site of Birka elucidate the understanding of socioeconomic networks of urban places in the Viking Age?**

- **Was the food provisioning of Birka direct or indirect?**
- **Did the three taxonomic groups of animals derive from the same place or different locals?**
- **How can animal mobility pertain to socioeconomic networks of the Viking Age?**

The research questions will be investigated through these methods:

- Stratigraphically chosen samples to determine potential change over time.
- Multi-isotopic analysis utilising $\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$ and $^{87/86}Sr$ to determine the mobility of domesticated animals and in addition, utilising radiocarbon dating (^{14}C) for age assessment.
- Using Bayesian Monte Carlo simulation statistics and boxplot models in R to quantify and methodologically interpret the isotopic results.

This thesis will be linking the isotopic analysis and the Bayesian statistical results with the broader theme of development of cities and their networks in prehistory. In addition using central place theory and word system theory as an anchor point for the development and definition of central places socioeconomic networks in prehistory (King 1985 [2020]; Kintigh et al. 2014). Using isotope analysis to shed some light of the food provisioning to such a place as Birka in the Viking Age, and how food provisioning and socioeconomic networks interlink. In combining these methods, a broader understanding of central places and their socioeconomic networks can be reached. The terms urban and central places will in this thesis be treated as interchangeable concepts, due to the stigma that often follows the urban definition.

Chapter 2. Theory

2.1 The urban debate:

Over the last decade, there has been a debate about what should be considered urban in the field of prehistoric city development. It has not only been a debate within the field of archaeology, but also within the fields of geography, anthropology and sociology (King 1985 [2020]; LaViolette and Fleisher 2005; Taylor et al. 2010; Renfrew and Bahn 2016:491). The search for broadly applicable characteristics has been at the forefront of the urban definition. This approach is rooted in a sociological definition of city development and was archaeologically first proposed by V. Gordon Childe in 1950 (LaViolette and Fleisher 2005; Fernández-Götz 2018). Consequently, excavations of cities like Mesopotamia, Rome, ancient Greece and Memphis in Egypt became universal models for city development and definition (LaViolette and Fleisher 2005:328; Fernández-Götz 2018:119). Within the field of archaeology Childe's (1950) urban criterion from the check list approach includes the following; an urban centre or town can only be defined when there is a legal law, the town should occupy a central geographic location, be densely occupied, have trade and craft production, have relations with the hinterland for control, monumentality, have mostly non-agrarian economy and specialised production of goods for trade, writing and scientific focus like maths (Childe 1950; Henning 2009:235; Holmquist et al. 2016:30). These checklist definitions have been shaping our understanding of the prehistoric urban towns and the urbanisation process and is generally applied within the field of archaeology.

However, dissatisfaction with definition arose when the difficulty of distinguishing between big villages and small towns became apparent as both can share certain characteristics (King 1985 [2020]). This is further elaborated on by LaViolette and Fleisher (2005:328) where they elucidate urbanism in the context of African development, highlighting there cannot be a one size fits all approach, as it would consequently leave out the urban development in much of the world and history combined (see also Kusimba 1999). The problem with the checklist approach developed by Childe (1950) is that it creates a sharp split between civilised societies and what he defines as 'savages' and 'barbarians' thus creating a pinnacle of development in civilisation in human history. This differentiation has been negatively utilised throughout modern times as well (Childe 1950; Pluciennik 2001; LaViolette and Fleisher 2005; Outram and Bogaard 2019:2).

Hence, another method to the check list approach developed, which can be classified as the functionalistic approach (LaViolette and Fleisher 2005:329). People like Max Weber in 1958 had significance for the field of archaeology, with linking urbanism to urban and rural interdependence (LaViolette and Fleisher 2005:330). In this regard, urban towns were recognised by the fact that they are non-agrarian (not agricultural) settlements, this mean a settlement that do not produce their own food (Skre 2012:58). Consequently, one can say that urban sites are food consuming while rural sites are producing (Gaastra et al. 2020:6). The response of the functional approach moved the focus away from what an urban town is, to what it does, treating a central place not as a single isolated aspect but a place connected to the outer world (LaViolette and Fleisher 2005:446). The checklist and the functional approaches have further shaped the field of archaeology in how the topic of urbanisation is investigated throughout prehistory.

2.2 Central place theory

Urban, in a basic definition of the word means city related, or some geographical area distinct from rural areas where assortments of people would gather and live for economic benefits (Smith 2014:307-309). The way in which urban places are involved in commerce and economic networks as the main way of labour are radically different from rural sites. Arguably the urbanisation process can be defined as the start of a consumer society (King 1985 [2020]; Taylor et al. 2010:2804; Carballo and Fortenberry 2015). The essential point to be remembered is that whether a central place is big or small, whether it is the main centre or just a central place for a region, it is always dependent on an integrated relationship with the hinterland and rural countryside, and it cannot stand on its own without extensive contacts (King 1985 [2020]:12).

This thesis will draw from the field of economics by using amongst others, the theory called central place theory. The origins of central place theory (CPT) came from Walter Christaller in 1933, published in 1966, his theory evolved around a hexagon pattern of interlinked central places in a spatial-hierarchical system model. Trading routes acted as a network between these specific central places (Christaller 1966; King 1985 [2020]). Many scholars have since then utilised this theory in many different ways, one of the more prominent ones being August Löch in the 1940's. Löch focused on the distribution of a good to be sold in a central place, and how that traced in the network (King 1985 [2020]:19-24). It should be stated that CPT has been criticised for its normative ways and different applications throughout different fields (Taylor et al. 2010; Fernández-Götz 2018:118-119). However, in later years a more revised and polished form of the theory has been utilised moving away from Christaller's normative set of criteria which often fell in the same trap as Childe's (1950) checklist of urbanisation, namely creating a split between civilised society and others (Taylor et al. 2010). The cornerstone in Christaller's original work in 1933 were the functional hierarchical interdependence between the central place and the surrounding hinterland (Skinner 1964; King 1985 [2020]:19). Christaller's theory revolved around some basic assumptions that central places are spread out on a homogeneous plain of uniform settlement, he does not however address how central places evolve (King 1985 [2020]:19). Consequently, for this thesis the theory will be applied in broad terms, and it is reduced to its fundamental principles in understanding the function of central places in connections with hinterlands and networks, and the focus will not be on the more mathematical spatial-hierarchical model. The essential elements of CPT are as follows:

- *A central place*
- *A central good*
- *A complementary region*
- *Interlinking network*

CPT revolves around the change of labour priorities and economic motivation. This means the move from an agricultural focus in rural sites to being freed from this task in the town (central place), where trade and economy is the dominant force of labour and economic surplus development for a broader network. The way of life in these central places differed to a rural site where the dominant force of labour evolved around the subsistence needs of the people connected to the farmstead (King 1985 [2020]:6; Carballo and Fortenberry 2015). *Agglomeration economics* is a general term used for how the cluster of economic activities in one place can benefit the economic development in general for a region, and it refers to a two-way link of interdependence (King 1985 [2020]:6). CPT is often used in modern economics to explain or elaborate on centres of economic abundance or development. However, it can be of relevance in the field of archaeology as well, when exploring systems and interdependence of prehistoric urban development and hinterlands.

2.3 Central flow theory:

Central flow theory (CFT) developed as a way to move away from the normative aspects of CPT. It has been argued that this theory developed as a post-processual response to the more positivist and processual CPT (Taylor et al. 2010). The theoretical idea of CFT derives from Meijers (2007) network theory as a rework of CPT. The basis of CFT theory is that while CPT at its core investigates interlocking hierarchical systems between central places, CFT focuses on the external process. To elaborate, while central place and hinterland connections remain relatively stable and detached from the outside network economy, no place developed on external relations only related to the hinterland, and that it is the flow of both commodities, people and tasks that develops a central place (Taylor et al. 2010; Vionis and Papantoniou 2019). CFT emphasises that it is the flow (of goods) that makes the places central whereas CPT emphasises that it is the places that makes the flow but the end goals are the same, to understand the dynamic of the central places (Taylor et al. 2010). In short, CPT only involves intercity hierarchal and hinterland processes, while CFT aims to incorporate the broader network, hence including non-local and outside connections, outside the immediate hinterland to understand and elaborate on the urban functions and the development of central socioeconomic networks (Taylor et al. 2010:2812; Vionis and Papantoniou 2019). These two theories should be viewed in tandem with each other and moving towards network centrality in understanding central places.

Therefore, both CPT and CFT can fit within the context of prehistoric urban towns and their socioeconomic networks, as it speaks of function, and not necessarily a check list for what a central place or urban city should entail. The scale and proportion should always be considered on the backdrop of the time in which the central place is analysed. As an example, if we were to put the scale of an urban town taken from today and try to fit an early urban town into that category, it would not be considered an urban town in that context (Callmer 1994:64). Consequently, it is important to always use the definitions given with the possibility to alter it to a different time, and yet see the connections of modern economic theory as is the CPT and CFT (King 1985 [2020]). It is also important to keep in mind that our modern definition of urban towns today vary from country to country, take for instance urban towns on the basis of inhabitants in Scandinavia that number needs to be around 500-1000 people, but in some places in China or America it can be 100.000 people (King 1985 [2020]; LaViolette and Fleisher 2005). Urbanism is how a place functions compared to the surrounding hinterland and the networks that makes it a central place.

These theoretical values from CPT and CFT fall in line with Immanuel Wallerstein's (1979) world-system theory as a concept, his work revolved around core and periphery of world systems, ergo networks (Chase-Dunn 1988; Sorinel 2010; Chase and Chase 2016). Similarly, to CPT and CFT the world-system concept is discussing as interlinking networks that connects different places, and the rise of capitalist societies. Wallerstein argued that world-systems are made of a multicultural and territorial division of labour, meaning that it was a necessity for the production of goods for exchange and trade to uphold the dynamics of the system between the core and periphery (Sorinel 2010:222). Consequently, in combining these theories as a consolidated and educative approach, it can serve as a great theoretical framework for the investigation of prehistoric central places and their networks, ergo core and periphery.

CPT and CFT, can then be connected to a small world system. The central places acted as nodes for the broader system at large. Think of it as the common phrase six degrees of separation, where people in the world are only separated by six links (Sindbæk: 2007b:21). This theoretical idea derived in archaeology from world systems theory by Chase-Dunn (1988). The central places would have been tightly connected, but also vulnerable. The loss of one central place would have ramifications not just for that place, but also for all the links that connected it. On the other hand, the loss of a farmstead connected to a central place would not affect the central place much, it could always redirect that link (Sindbæk 2007b). The archaeological material of foreign character found in these places do not symbolise a rare commodity, but rather things that once was readily available, due to these networks (Sindbæk 2007b:66; Lund and Sindbæk 2021:22). Further, it underlines that some places might have specialised on the distribution of a certain commodity, which would result in some places having more of certain things, while other central places might have less of that same commodity (Sindbæk 2007a, 2007b). This web of central places supplied the socioeconomic networks of exchange, goods, raw materials, and people that travelled between them, in a small world system.

A good example of CPT as a proxy for urban development is the urban places on the Swahili coast of Africa. Historically the Swahili had been connected to maritime activities which were an early focus point in studying this culture and society (Kusimba 1999; Reid 2000). The argument is that the Swahili became maritime and the urban process started with a bigger more well-known cultural influence, in this case the Islamic culture during the Iron Age, see Fleisher et al. (2015) for more info. This led to a distinction, almost as a split between the coastal connections and the hinterland, treating the hinterland as an unconnected and undeveloped concept that is unattached to the question of central places and urbanism.

However, as Kusimba and Walz (2018) describe it, a check list adherences will leave out many complex aspects of cultures and societies in development studies (Fleisher et al. 2015; Kusimba and Walz 2018). The research conducted in Africa has evidence of alternative forms of urban development, not formed on the basis of hierarchy, monumentality or politics, but stemming from a variability of demands, including centrality caused by the trade economy (LaViolette and Fleisher 2005:334-337). These places that developed on the Swahili coast, also known as stone towns, served as central places connecting the hinterland with the broader socioeconomic network. The fundamental principle in which such central places developed varies from place to place, which challenges the classical approaches to centrality and urbanism, opening it up to variability and individuality (LaViolette and Fleisher 2005:350-353). Stone towns were responsible for the flow of goods through these central places. The overall control and coordination of the flow of goods came from these towns, and at the same time they were totally dependent on the hinterland. Controlling the trade between different actors on a broad scale, contributed to a broader socioeconomic network, in which these towns were central (LaViolette and Fleisher 2005:339,340). Placing the Swahili stone towns in a small world system connected with the principles from both CFT and CPT, where these central places were undoubtedly connected to each other and the hinterland for its status, flow of goods and subsistence, while the hinterland took equal benefit of the central connection, goods and labour.

The takeaway is that the interaction between different groups of people, different socioeconomic pathways and interconnections is essential for these places to exist. It draws on the fact that towns, now and in the past were connected to the hinterland in an interlocking network of interdependence and the development (Skre 2012). This pulls the focus away from the maritime, coastal, monumental, singular and hierarchical aspects of an urban defined place or culture, instead connects it to a broader socioeconomic network and the function of these towns as central places for the region and the hinterland, with an individual development for each place (LaViolette and Fleisher 2005; Skre 2012; Kusimba and Walz 2018:430) .

2.4 Testing centrality in the archaeological record

Scientific methods, like isotope analysis can shed further light on these networks. When investigating people's movements between central and rural places or focusing on one economical aspect like animals, these networks can be tied in with geographical places and extents. Scientific methods have opened avenues for tracing the previously untraceable (Lund and Sindbæk 2021:23). In examining food provisioning strategies to these central places, it can trace the pastoral economy, and trade patterns in how people utilised the landscape (Arnold et al. 2018:1,2). Food provisioning economies are greatly affected by central place adherence. When the need for the production of goods became the main source of labour, and food became secondary, subsistence would usually be received through an indirect provisioning, which in turn also would be centralised (Zeder 1988; Zeder 1998). The animals selected would be the ones that had the most meat yield, hence cattle would be preferred over sheep, and private and direct provisioning would be discouraged by the provisioning system to encourage consumer dependency (Zeder 1988:12; Zeder 1998).

One such example is the investigation of the Bronze Age urban town of Tell es-Safi/Gath in Israel. This study describes the importance of understanding food provisioning to early cities as part of their development (Arnold et al. 2018). The study aimed to investigate the mobility of sheep and goats (Caprinae). The study utilised isotope analysis to determine what kind of food provisioning systems were connected to the socioeconomic network of the town. This analysis shed light on the pastoral economy, and the transition from producer to consumer economy in understanding the food provisioning to early urban places and how it connects the town and hinterland, also described as core and periphery (Arnold et al. 2018).

The results of the study by Arnold et al. (2018) was that food provisioning came from areas controlled by the city, shedding light on the control or connection of the city outside the immediate city boundaries and connecting it in a broader socioeconomic network to the hinterland and not just the trading network (Arnold et al. 2018; Gaastra et al. 2020:5). Consequently, a network of exchange is a necessity for a community to integrate specialised production, hence export and import of domestic livestock, which again can be interpreted as an increasing economic specialisation with the development of urban places. However, the study by Arnold et al. (2018) concluded that the food provisioning was mainly local, a direct provisioning compared to the network of trade. This is indicated by little variation in the isotopic data, concluding with a homogenous diet for the sheep and goats (Arnold et al.

2018). The conclusion was, while the trade was connected to a broader network, the food provisioning remained local to the site in question.

Central places have links to other places and including the hinterland, and the economies of these places were driven by the demand for goods and force of labour. The work done contribute to the collective whole, and not just for personal gain (Zeder 1988:8-10). Consequently, subsistence became the secondary product, so the main focus in these places would be production of trade objects (Zeder 1988; Callmer 1994:60-66; Skre 2012). In Scandinavia the urbanisation process is generally categorised into two stages, stage one with emporia that were established in the 8th century and royal towns established from the 11th century onwards (Runge and Henriksen 2018:2,19,23). In the Viking Age, places that contrasted the rural way of life developed, like Birka, Ribe, Hedeby and Kaupang (Kalmring and Holmquist 2015:58). These towns were centres of economic functions for the hinterland, clearly relying on the networks, but more importantly they depended on the hinterland for subsistence and ergo survival. The central places have a function of centres of craft production and dispersing it to and between other places. The archaeological excavations of people with different origin sheds the light on the multi-ethnicity of these places. The Viking Age towns were often close to waterways which acted as the prehistoric highways, connecting them to the broader network of the time (Holt 2007; Kalmring and Holmquist 2015; Runge and Henriksen 2018).

In utilising scientific methods as a steppingstone to expand the concept of urban thinking and central places, more elements of the socioeconomic networks can be unravelled. In tracing one component of their network economy like animal mobility, much can be understood about their socioeconomic and development in the urban process (Fernández-Götz 2018:118,148-149). Utilising theories such as CPT, CFT and a small world theory, combined gives the overall understanding of prehistoric development a better context in which scientific methods can be the proxy.

Chapter 3. Background

3.1 Environment:

Archaeologists get a deeper understanding of questions related to mobility, subsistence and environment by incorporating the broader environmental context of archaeological sites (Amorosi et al. 1997; Wright 2017b:1). When utilising isotopes, different factors from the environment comes into play, also known as isoscapes, which is the isotopic distribution in the landscape, and the information about, geology, plant life and water levels are important factors to consider when interpreting isotopic values. As such, different parts of the natural environment will have to be taken into consideration throughout this thesis, which also forms the general background for interpretation of the results.

The Viking Age was a time when stock farming became more utilised relative to the preceding Iron Age, and the animals most commonly utilised were cattle, sheep/goat and pig (Hansson 1978; Ericson et al. 1988; Wigh 1998; Wigh 2001; Risberg et al. 2002). Pigs, sheep or goats have often been utilised as a private source of food provisioning as they can be kept in small spaces close to houses (Zeder 1988; Zeder 1998:64; Wigh 2001). Pigs are omnivorous and were often feed scraps from the household. Cattle need larger areas for grazing, and more water than pigs and sheep (Zeder 1998:64; Wigh 2001; Balasse et al. 2002:925). Sheep are grazers and eat much of the same food stuffs as cattle, while goats are mixed browsers (Zeder 1988; Arnold et al. 2018:8). These animals inhabit different economic niches; cattle did not only provide meat, but also milk, labour as draft animals and leather. Sheep were utilised both for meat and wool, goats were utilised for milk, while pigs were utilised for meat alone (Zeder 1988:12; Zeder 1998; Wigh 2001).

Common plant species found in Scandinavia during the Viking Age include barley (*Hordeum* sp.), common wheat (*Triticum* sp.) and rye (*Secale* sp.) which are cultivated crops, commonly utilised for bread and porridge (Hansson 1978). Other economically useful plants like Jackob's Ladder *(Polemonitum caeruleum)* which is a natural flower today in Sweden and Finland, was utilised as a gardening plant in the Viking Age (Risberg et al. 2002:451). Different plants from typical meadows like daisies (*Asteraceae liguliflorae)*, Chenopodiaceae, clover (*Trifoliutm* sp.), cruciferous vegetables (Brassicaceae sp.), herbs (eg,.*Centaurea* sp.) and weeds (*Centaurea jacea*) were found in macro samples from the site (Risberg et al. 2002; Rohde Sloth et al. 2012:28). Herb plants like orache (*Atriplex patula)*, shepherd's purse (*Capsella bursa-pastori)*, white goosefoot *(Chenopodium album)*, nipplewort (*Lapsana communis)* thrive in open environment and naked barren soil. A type of daisy (*Bellis perennis)* and rattle (Rhinanthus sp.) have also been identified, and associated with grazed areas, however these two were the only species of this sort found in the study area. Plants like hops and hemp (*Humulus lupulus)* and celery (*Apium graveolens)* are plant species usually not found the northern hemisphere in the Viking Age, and would have been imported (Risberg et al. 2002:451).

In Sweden the geology is for the most part made up of rocks from the Fennoscandian Shield, which is a craton of mantle rock, and is one of the oldest rock formations in Europe (Risberg et al. 2002; Price et al. 2014; Blank et al. 2018; Price et al. 2018:30-32). The geology of Sweden is generally made up of these older rock formations, however there are variation of rock types throughout the different regions of the country (Blank et al. 2018). The sediment type that dominates northern and central Sweden are derived from Precambrian rocks (Blank et al. 2018:18; Price et al. 2018:30). According to Risberg et al. (2002) the bedrock that makes up the island of Birka consists of gneisses and granites, in addition to deposits of clay, silt and till from the late Weichselian Ice Age.

It follows that the food web would be impacted from the fact that the study area is situated in an archipelago. Surrounded by a fjord, where there is a mix of saltwater from the Baltic Sea and freshwater from inland, ergo brackish water (Wigh 2001; Price et al. 2018) . The Baltic and the fjords going inland in Sweden from it would have contributed a great and important food source, with both freshwater and ocean-going species for utilisation. The Baltic influence is one of the most important ecological factors to consider when interpreting isotopic values from this area (Liden and Nelson 1994:14-15). During this time the water level was retreating due to isostatic uplift of land, and the shoreline would on average have been five metres higher than today (Risberg et al. 2002; Renfrew and Bahn 2016:238; Price et al. 2018).

3.2 The Viking Age:

The general way of life for most of the population were focused around rural farmsteads and family groups. The term rural is for this thesis defined as an agrarian society, which includes communities living around a single farmstead (Kalmring and Holmquist 2015; Kalmring 2016:15; Croix et al. 2020). Consequently, everyday activities consisted of farming and cultivating for their own sustenance needs (Kalmring and Holmquist 2015). During the

Viking Age stock farming of livestock were also expanding in utilisation (Risberg et al. 2002:445; Kalmring 2016:15; Croix et al. 2020:1-4). However, it is also during this time the change from producer to consumer and a hint of capitalist society starts to take form in Scandinavia (Helle 1994; Skre 2012). The Baltic region had an increase in trade, and several central places developed to act as nodes for these trading networks (Callmer 1994:63; Kosiba et al. 2007). These places were urban in character, for reference, urban is a place where people do non agrarian activities to sustain themselves, making the economy non agrarian (non-agricultural) based economy (Holt 2007; Carballo and Fortenberry 2015; Runge and Henriksen 2018). It is this reference that is used as point of departure here.

3.3 Birka:

During the Viking Age many towns, hubs and nodal points grew and flourished in Scandinavia and around the Baltic Sea, Birka, Kaupang, Ribe and Hedeby were the main ones in Scandinavia (Helle 1994). These places developed in strategic positions and played a role in the elaborate trading network of the Baltic and Scandinavia (Callmer 1994:60-64). The development of these towns was one of the most important societal changes that happened during the Viking Age (Croix et al. 2020). Consequently, these places had a plethora of people from different places of the world, including places as far as the Mediterranean and far eastern Europe (Croix et al. 2020:1-3). Situated on archipelago called Björkö in what is today the Mälaren region of modern Sweden, Birka flourished between 750-975 CE (Risberg et al. 2002:447). Which means that the earlier settlement and activity at Birka somewhat predates the historically set date of the start of Viking Age in 793CE. Contemporary written sources like *Vita Anskarii*, the *Royal Frankish Annals* described the place as *portus* which means place of trade. *Vicus* which means trading place and merchants settlement, *civitas* is often used in describing towns, *urbs* refers to a stronghold and *oppidum* trading place and town (Helle 1994:20-30; Sindbæk 2007b). It has also been described in these works that Birka was one of the first places in Sweden in which there was an attempt to convert the population to Christianity through missionary work (Helle 1994:20-30; Wigh 1998; Ambrosiani 2013; Holmquist et al. 2016).

During the Viking Age the sea connections from Birka reached all the way to the Baltic Sea. This meant that one could sail for quite some distance up the different fjords into what is today Sweden, making the place geographically central, with connections to the Baltic, Old Uppsala and Vendel along the waterway Fyrisleden (Kalmring and Holmquist 2015; Price et al. 2018). This ideal position also adds up with the archaeological material of foreign origin found at the site of Birka which indicates far reaching trading connections (Wigh 1998; Risberg et al. 2002; Kalmring and Holmquist 2015; Price et al. 2018). The archaeological material gives insight into a place that had connections with Western Europe, Dorestead and the West Slavic coast. However, this shifted during the later periods of the town to the Carolingian empire and Friesians, also Scandinavia, Russia and Finland and as far as the Indian Ocean (Wigh 2001:19,20; Linderholm et al. 2008:447; Kalmring and Holmquist 2015:61; Roslund 2020).

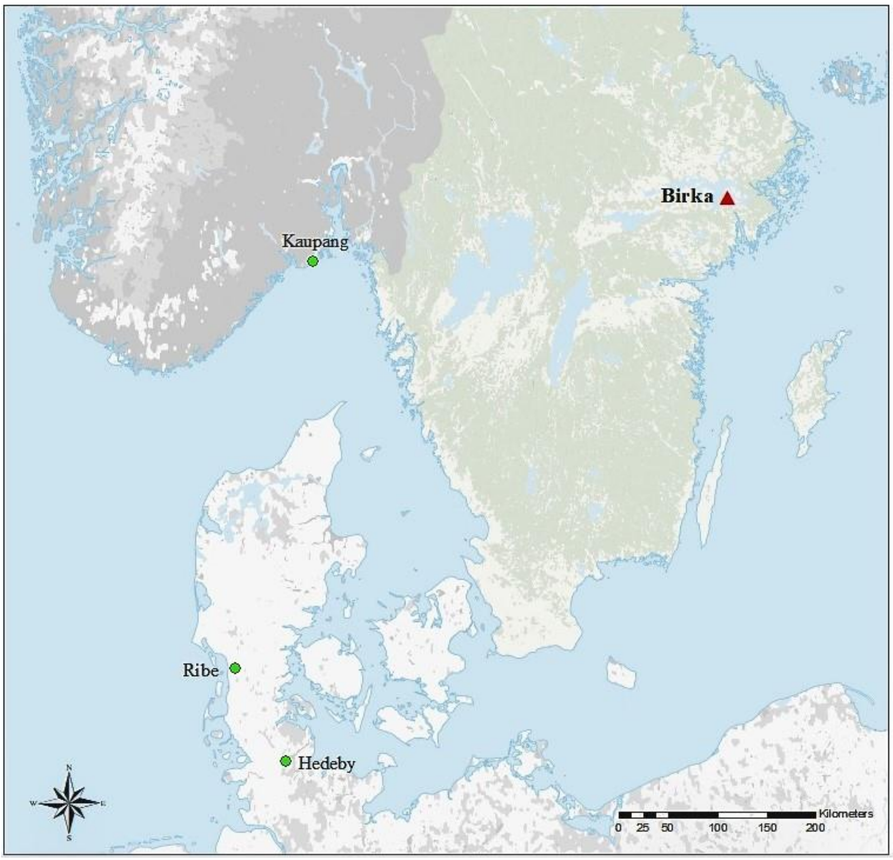

Figure 1: Map of the Scandinavian places that developed during the Viking Age.

The primary settlement area at Birka is today referred to as the ‘Black Earth’ and it is a nutrient-rich cultural soil layer, that contains traces of heavy anthropogenic activities. The excavations have yielded information about activities such as bronze working, furs, textiles, metal working, bead making, glass making, and other craft production activities (Wigh 2001:19,20). The settlement was fortified, and the fortification surrounded the town area (Kalmring and Holmquist 2015; Hedenstierna-Jonson 2016:27; Price et al. 2018:21).

It is estimated that the population of Birka during the Viking Age was around 500-1000 people per generation (Risberg et al. 2002). Further, is has been estimated to be around 4500 to 5000 human graves in total at Birka, the grave mounds surrounds the settlement area (Price et al. 2018:22). During Birka’s period of human settlement, these mounds would have encircled most of the town. Material from these graves indicates people from many different places were buried there. Research of sex and age from these graves, concluded that few children were buried at Birka, and the division of female and male graves are approximately equal (Sundman and Kjellström 2013:4459,4460; Hedenstierna-Jonson 2016:23). In the hinterland of Birka known today as the Mälaren Valley, it has been estimated that people lived around farmsteads, with perhaps 10 people connected to the farmstead at most, in family groups estimated from graves (Sundman and Kjellström 2013; Price et al. 2018). The surrounding countryside and the Mälaren region had on estimate from excavations, 3000 to 5000 settlements in the Viking Age. Jewellery, bronze, glass and other objects from Birka has been found in this surrounding hinterland (Ambrosiani 2013:35).

The position of the town on an island, has been calculated to have been too small to sustain the number of people living there, and thus Birka had their subsistence needs met from other places (Hansson 1978; Ericson et al. 1988; Wigh 1998; Wigh 2001; Risberg et al. 2002). The harbours that once connected Birka to the flourishing trading network, are today found on dry land (Risberg et al. 2002:446; Price et al. 2018). This is attested to by the fact that Birka consisted of two separate islands in the Viking Age. Consequently, the passage from the Baltic Sea closed around 1000-1300 CE due to the isostatic uplift. In addition to closing the sea path from the Baltic, it also led to the water level around Birka sinking by around 5m, resulting in the two islands joining and thus having a larger land area today than in the Viking Age (Risberg et al. 2002). Even though Birka ceased to exist as a settlement around 975 CE, it is thought that the water regression caused by the isostatic uplift affected the settlement, long before the closing of the Baltic passage. According to Risberg et al (2002), the diatom flora gradually changed to a more freshwater based as opposed to a mix of salt and freshwater (brackish water) which coincides with the closing of the Baltic passage **(Figure 2)**.

Figure 2: Map from Geological Service Sweden SGU, Topographic background: GSD-Terrängkartan© Lantmäteriet. Birka (Björkö) left water level 950 CE, right present-day water level.

3.4 Research:

Birka was a multi-ethnic place, research of the human population buried at Birka were indicative of foreigners, from places like Finland, the Baltic regions, Norway and other parts of the world (Linderholm et al. 2008; Price et al. 2018). Isotopic studies have also pinpointed people of different geographical origin which further supports the multi-ethnicity of the place (Price et al. 2018). People of different statuses were also buried at Birka, this is evident by the material goods found in graves, and archaeological material of foreign origin which has been found during excavations (Linderholm et al. 2008; Price et al. 2018). In addition, the isotopic research of the human population has concluded that some people had different diet and different status and that there was a different based on grave type, which further supports Birka as a multi-ethnic place (Linderholm et al. 2008; Price et al. 2018; Roslund 2020).

Further, a zooarchaeological study conducted by Bengt Wigh (2001), interpreted the animal bones excavated in the Black Earth settlement area of Birka. His investigations shed light on a fur trade, which were rather consistent throughout Birka's existence. Further, for the domesticated taxa it was concluded that cattle were most likely imported as adult animals, pigs were slaughtered quite young and could have been kept in pens on the island. Sheep and goats were common in the earlier layers, however a shift happens in the 9th century where the consumption of beef ergo cattle became the dominant taxon group in the archaeological assemblage (Wigh 1998; Wigh 2001:136-139). The collection of animal bone material from Birka is one of the most comprehensive assemblages from an urban Viking Age town in Scandinavia (Wigh 1998).

3.5 Excavations:

The research and excavation history from Birka go as far back as the 17th century. However, Hjalmar Stolpe's excavations between 1871-1874 and 1878 which focused on the grave mounds set the stage for the modern research into Birka, and were probably for its day, a more well-recorded excavation. However much of the documentation from his excavations has been lost (Kalmring et al. 2021:3-4). Stolpe's excavations brought to light the possibly urban character of the site due to the vast amount of non-local archaeological material found during excavation (Kalmring 2012:261; Hedenstierna-Jonson 2016:23).

Björn Ambrosiani and Birgit Arrhenius later excavated the maritime structures from 1969 to 1971, which are now on land due to the isostatic uplift that happened by the end of the Viking Age **(Figure 2).** These excavations contributed a great deal to the knowledge of Birka as a potential urban town with an extensive trading network (Ericson et al. 1988; Callmer 1994:50-70). It was during this excavation that the stone construction called *"stenkistan"* was excavated, believed to be the foundation of the harbour facilities (Ambrosiani 2013). This excavation gave new insight into the shoreline and the foundations for jetties and how they seem to have been in constant construction and change, interpreted as a way to deal with the changing water level, or the expanding settlement area as the town grew (Callmer1994; Hedenstierna-Jonson 2016:26).

The excavations in the Black Earth site in 1990/1995 conducted by B. Ambrosiani, provided a more comprehensive view of the settlement area. Methods such as sifting to retrieve smaller fragments of archaeological material were utilised for the first time. The archaeological material recovered were, pottery, beads, glass, craft objects and a vast amount of animal bones, approximately six tones were excavated (Ericson et al. 1988; Ambrosiani and Erikson 1996; Wigh 1998; Wigh 2001; Ambrosiani 2013; Sundman and Kjellström 2013). The Black Earth site was interpreted as a heavy anthropogenic waste stratum derived from the main area of settlement and activity during Birka's occupation (Risberg et al. 2002).

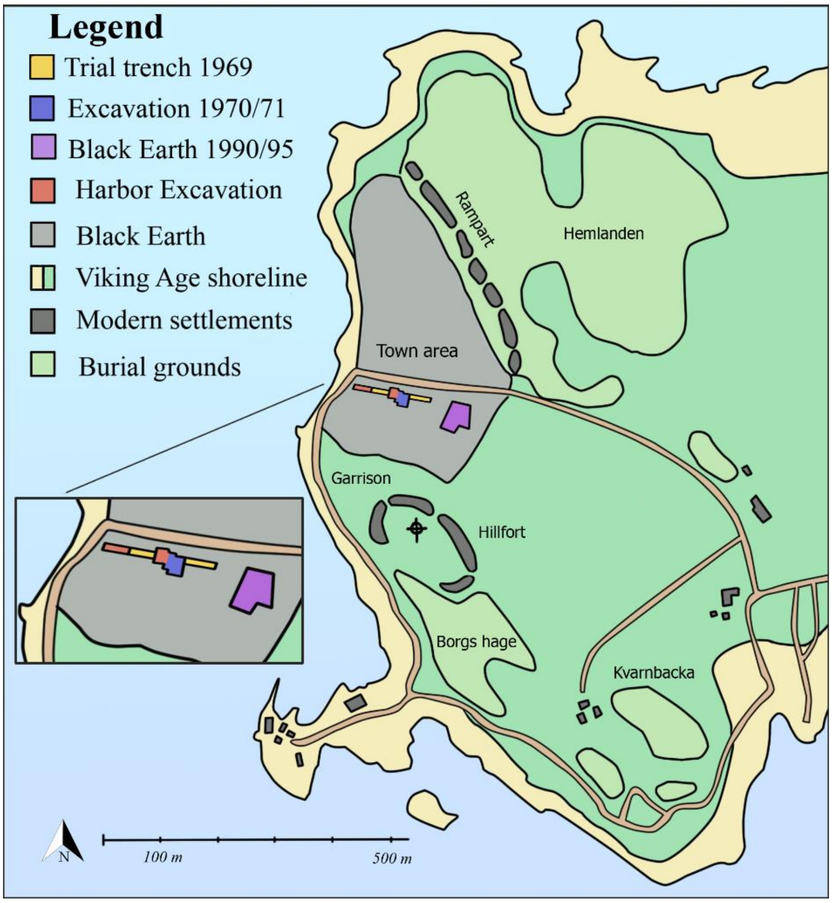

Figure 3: Map of the main excavations, Black Earth and Harbour excavations. Map by Molly Wadstål adapted from Price et al. (2019).

3.6 The Harbour excavation 2015/2016:

Most recently, the excavations carried out by Sven Kalmring and Lena Holmquist in the Harbour area between 2015-2016 yielded new insight into the harbours of Birka and gave a better context to the prior excavations conducted in the vicinity (Kalmring et al 2021). This excavation was a continuation of the 1970/1971 excavations in the harbour basin area **(Figure 3)**. The Harbour excavation yielded a vast amount of well-preserved animal bone material derived from waste fills probably dumped into the harbour area. Further, artefacts like broaches, beads, pottery, metal objects and glass were found throughout the excavated layers (Kalmring et al 2021). Archaeological findings included an oval broach of Peterson type 37 which is usually dated to the 9th century, found in layer 23/IV (Kalmring et al: 2021:56). The excavation area was divided into different subplots, given a PQ number and the excavation were sequential given different L number for the different layers. The stratigraphic layers of the Harbour excavation were dated utilising a relative dating seriation according to Johan Callmer's 1977 bead chronology **(Table 1)**.

Bead dated layers:	**Callmer's 1977 bead chronology:**
	BdPI 790-820CE
L32 prior to 845 CE	BdP II 820-845CE
L35, L30 845-875CE	BdP III 845-875CE
L37, L36, L23/V 875-905 CE	BdP IV 875-905CE
	BdP VII 905-935CE
L23/IV 935-955 CE	BdP VIII 935-955CE
	Bdp VI 955-965CE
L23/I-III and L17 965-990 CE	BdP IX 965-990CE
	BdP XII 990-1000CE

Table 1: Callmer 1977 chronology info from Kalmring et al (2021: 94-95). The original acronym is BP=bead period. However, this was changed here to BdP to avoid confusion with BP (before present) when discussing the radiocarbon ages conducted for this thesis.

L31 was considered the oldest layer and consists of marine clay, L30 was situated immediately above this marine clay layer and it seemed to be a geological stratum with some of the earliest elements of anthropogenic activities from the harbour basin (Kalmring et al. 2021:66). L32 was a silty sandy layer. Layer 23 was the biggest layer and were divided into sub sections L23 I-V. L23 layer has been interpreted as the anthropogenic waste-layer, accumulated by anthropogenic activities of deliberate waste, possibly thrown into the harbour basin throughout Birka’s existence as a town (Kalmring et al. 2021). L23 also contained large amounts of fire cracked stones, which has been interpreted by the excavators to have been a deliberate attempt to build up the harbour basin (Kalmring et al. 2021:66). L36 was a single time dumping event embedded in L23; the most remarkable article from this layer was a fully preserved cow skull with a blow to the forehead. L37 was an elongated layer just above the geological layers, and at the bottom of L23, interpreted as an attempt to install a jetty post (Kalmring et al. 2021:64-85; **Figure 4 and 5**).

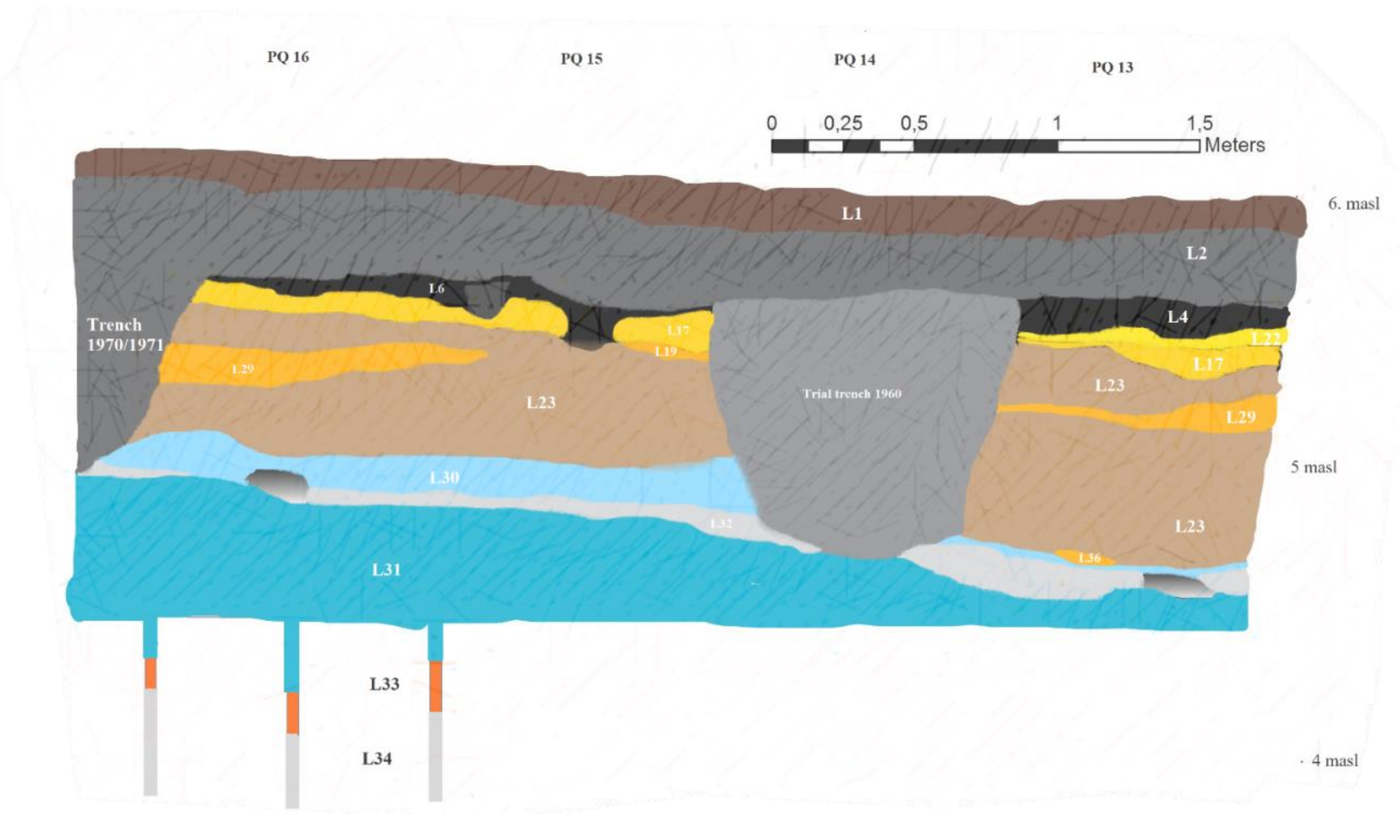

Figure 4: Drawing of the different layers 2015/2016 excavation, adapted from figure 60a Kalmring et al 2021. Schematic drawing of the different layers (Kalmring et al 2021).

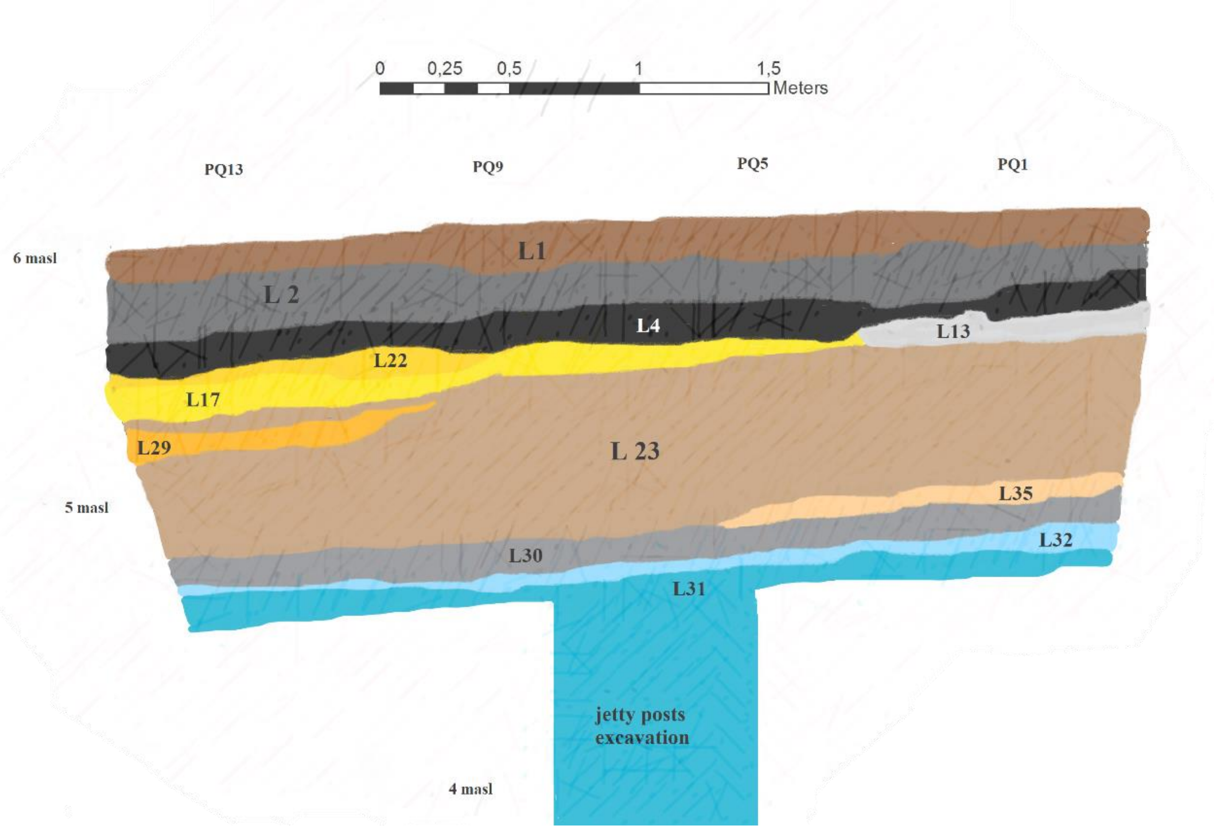

Figure 5: Drawing of the different layers 2015/2016 excavation, adapted from figure 61a Kalmring et al 2021. (Kalmring et al 2021)

3.7 Osteological results from the 2015/2016 Harbour excavation:

The vast amount of animal bone material utilised for this research were excavated throughout the layers of the harbour basin close to the Black Earth and settlement area. The archaeological bone material was osteologically analysed by Molly Wadstål (fellow UiO student) in 2020 and forms the foundation for the present isotopic investigation. Her results indicated that the bulk of the assemblage consisted of cattle bones, followed by pig, and with sheep the least represented overall (Wadstål 2021). The bones had butchery and cut marks which varied between the layers and were indicative of a more standardised butchery technique from L30. Cattle and pigs were for the most part represented by the entirety of the skeleton, while the sheep material was fragmented and less represented across the layers (**Table 2**; Wadstål 2021).

English name	**NISP**	**Weight (kg)**
Cattle	1249	23
Pig	803	4.4
Sheep/Goat	278	1.3

Table 2: Total NISP (NISP= Number of Identifiable Specimens) from the analysed osteological material, table by M. Wadstål 2021.

Chapter 4. Isotopes

4.1 Isotope analysis:

Isotope analysis can help to elucidate the mobility of animals and determine the extent of the animal economy of Viking Age places. To understand what isotopes can do, one must start with what they are. Chemical elements are defined by their atomic numbers, which relates to the number of protons in the nucleus, while the atomic mass refers to the number of protons and neutrons in the nucleus, also known as the nucleon number (Chang 1998:44-45; Ben-David and Flaherty 2012). Take for example ^{13}C, 13 = indicates mass number and the number of protons and neutrons the element has, while C is the atomic symbol for the element carbon (Chang 1998:45). The protons in the nucleus are positively charged, the neutrons are neutral and both are surrounded by negatively charged electrons (Brown and Brown 2011:80; Wright 2017b; Outram and Bogaard 2019:51). If one varies the number of protons, the atoms become a different element altogether. However, if the number if neutrons change it becomes a different isotope but of the same element, for example ^{13}C or ^{12}C which are both carbon but with a different number of neutrons. In varying an atoms number of electrons you get different ions, ions can be defined as a molecule with a specific charge due to loss or gain of electrons (Brown and Brown 2011:80). In most cases isotopes will have the same chemical properties, but it will have a different mass. Most elements are found naturally as different isotopes in a ratio which is referred to as isotopic abundance. The ratios for different isotopes of the same element are relatively stable (Ben-David and Flaherty 2012).

There are two different categories of isotopes, unstable isotopes which decay over time through radioactive decay and stable which do not decay over time. Most of these isotopes exist in nature, however not in equal amounts (Brown and Brown 2011:80,81; **Table 3**). For instance the unstable isotope ^{14}C is generated by the collision of negatively charged cosmogenic particles with nitrogen (^{14}N) in the atmosphere, and return to a stable form due to radioactive decay (Bowman 1990). The isotope ^{14}C decays via the emission of subatomic particles, this emission can be described by its half-life, which for this isotope is 5730 ± 40 years. The half-life can be explained by the exponential function:

$$N(t) = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

Where N(t) is the number of radioactive particles present at *t* time and half-life of the specific isotope is described by $t_{½}$ (Bowman 1990). The reason for the decay is that all living things take up carbon including ^{14}C during their lifetime, and when an organism dies, the uptake of ^{14}C stops, and starts to decay. Unlike the stable isotopes of ^{12}C and ^{13}C which remain in their stables state, the amount of ^{14}C relative to ^{12}C and ^{13}C will therefore decrease as a function of time (Chang 1998: 54-57; Bowman 1990:10.11; Brown and Brown 2011:80,81; Wright 2017a). This principle is valuable in archaeology for determining age and is known as radiocarbon dating and is one of the best ways in establishing the chronology of archaeological sites.

The radiocarbon method for determining age of archaeological specimens has given the field of archaeology a huge advantage, however the ^{14}C in the atmosphere is not constant, causing the measurements of ^{14}C in archaeological material to potentially show incorrect ages (Wright 2017a). One such example is the Libby Effect which happened after the detonation of nuclear weapons in the 1940's, which released massive amounts of ^{14}C into the atmosphere, and caused the dates from this time period to be inconsistent. Thus, there is a need for calibration curves that can correct for these known inconsistencies, and programs such as OxCal can be used for these calibrations (Wright 2017a; Reimer 2020) .

Reservoir effects need to be taken into consideration when interpreting radiocarbon dates. Reservoirs are a result of the circulation and uptake of dead forms of carbon ergo inorganic carbon which are depleted in ^{14}C, in most cases carbonates by aquatic mammals are taken up by other organisms. Reservoirs effects tends to make radiocarbon ages older than what they truly are. (Sayle et al. 2016; Wright 2017a; Dury et al. 2018). There are two types of reservoir effects, one for freshwater (FRE) and one for marine (MRE), these are ^{14}C offsets of CO_2 in the atmosphere and the reservoirs. MRE also occurs due to the residence time of the radioactive decay where old carbon is recycled, which is longer in the ocean than on land (Wright 2017a:306). FRE is the low input of ^{14}C activity carbon or the restriction of the CO_2 exchange in water (Reimer et al. 2009; Sayle et al. 2013:532). The global average for this is 400 ^{14}C years, ergo such samples will appear 400 years older than their true age (Sayle et al. 2013:532). This means that animals that have lived in aquatic environments or consumed a lot of marine protein will reflect a possibly older date when radiocarbon dated.

Fractionation of isotopes occurs when metabolic or minerogenic processes between heavier or lighter isotopes create different isotope ratios (Brown and Brown 2011). Fractionation is considered the basis for understanding stable isotopic variation (Katzenberg 2008:416). The fractionation process can be described as an enrichment of one isotope relative to another.

The two types of fractionation are called kinetic fractionation and equilibrium fractionation. Kinetic fractionation is a physical or chemical reaction such as diffusion, evaporation and condensation. This process favours light isotopes compared to heavier isotopes, it is when a single molecule changes phase a phase is i.e. liquid to vapor (Ben-David and Flaherty 2012:315). One such example of kinetic fractionation is the evaporation of water, when water evaporates from for instance the ocean it results in oxygen (^{18}O) fractionation with 13‰, because the lighter oxygen isotopes i.e. ^{16}O evaporates faster than the heavier isotope of ^{18}O (Ben-David and Flaherty 2012:315). Equilibrium fractionation is when two physical phases and a differential exchange of isotopes, which are in equilibrium with each other (Brown and Brown 2011; Ben-David and Flaherty 2012). The reason for this is that chemical equilibrium reactions differ in their isotopic ratios, heavier isotopes then creates stronger bonds than lighter isotopes with the substrate (heavier) or product (lighter) (Ben-David and Flaherty 2012:315).

Element	Isotopic mass number	Relative to nature*
Carbon	12	98.93%
	13	1.07%
	14	one part per trillion, half-life 5730 ± 40 years
Nitrogen	14	99.64%
	15	0.36%
Strontium	84	0.56%
	86	9.86%
	87	7.00%
	88	82.58%
Sulphur	32	95.02%
	33	0.75%
	34	4.21%
	36	0.02%

Table 3: Isotopes and their mass number relative to nature, data and table adapted from Table 6.1 Brown and Brown (2011). *Relative to the internationally set standards Vienna-Canyon Diablo Troilite (VCDT) for ^{34}S, Air (AIR) for ^{15}N, Vienna Peedee Belemnite (VPDB) for ^{13}C, States Geological Survey *Tridacna* for $^{87/86}Sr$ (Trust and Fry 1992; Ben-David and Flaherty 2012:314; Nehlich 2015).

The common way to analyse isotope ratios from samples has been the use of isotope-ratio mass spectrometry (IRMS) to measure for instance the isotopes of ^{13}C, ^{15}N and ^{34}S, solid or pulverised samples are converted to gas state through combustion (Wright 2017b; Hamilton et al. 2019; Sayle et al. 2019). The gases that this process produces are then ionized, after that they go through a magnetic field that drops the charged ions into a Faraday collector which then catches the ions generating a current that can quantify the amount of each measured isotope in the archaeological sample. The magnetic field separates the charged ions based on their masses, which analytically is known as mass-to-charge ratio (m/z) (Brown and Brown 2011:87; Ben-David and Flaherty 2012; Wright 2017b).

For the data to be interpretable, the values of archaeological samples are measured against an internationally established reference standard **(Table 3)**. The standard most commonly used for ^{13}C is called Vienna Peedee belemnite (VPDB) a marine carbonate from coastal South Carolina (Ben-David and Flaherty 2012). Measured isotope ratios are expressed as parts per mille (‰). The delta (δ) is representing the function of the difference in comparison from the measured ratio of an isotope to the internationally known standard. The δ isotope values are commonly expressed as enriched or depleted compared to their source/standard. Depleted means that the δ value is less than the set standard, and enriched if it is more than the set standard (Brown and Brown 2011:80,81; Ben-David and Flaherty 2012:314). For instance, the δ describes the relationship between ^{13}C and ^{12}C relative to the standard VPDB, and ^{15}N and ^{14}N ratio in the measured sample relative to the standard AIR (Brown and Brown 2011:81; Roberts et al. 2018:362; Outram and Bogaard 2019:53; **Table 3**).

4.2 Isotopes in archaeology:

The natural abundance of the heavy and light isotopes on earth works as a marker system, which is possible to trace up the food chain of all living organisms (Ben-David and Flaherty 2012:317). To determine past diets using isotopes, any organic material can in principle be used however, it is most common to extract collage from bone or dentine from teeth. Collagen and dentine are the protein matrices formed in bone and teeth, and it is from this that isotopic signatures of dietary information can be measured (Ben-David and Flaherty 2012; Outram and Bogaard 2019:53). Further, it is important to keep in mind that bone has a turnover time during biosynthesis when the collagen renews itself, which for cortical bones (long bones) is 10-15 years and trabecular bones (ribs) is 2-5 years. However, dentine in teeth is set when it is formed and does not reconstitute (Bentley 2006; Ben-David and Flaherty 2012). Due to this measuring values from dentin can give sequential information over an individual's life during the teeth's formation processes, while the measurement from bone gives information of the last years of an animal or human's life (Balasse et al. 2001:235-236; Brown and Brown 2011:86; Guiry et al. 2016). Diagenesis is the effect of either external or internal factors such as: burial environment, soil type, pH, erosion, bacteria, crystallisation and other such factors that can alter or disturb the isotope values of the in vivo isotope values of samples (Brown and Brown 2011; Nehlich 2015; Wright 2017a:306; Kendall et al. 2018; Roberts et al. 2018:363,364; Outram and Bogaard 2019:53).

4.3 Carbon isotopes:

The principle of carbon isotopes starts at the bottom of the food chain with the photosynthesis of plants in which plants convert carbon dioxide (CO_2) into sugars using sunlight in what is known as the Calvin Cycle to split carbon from oxygen. There are two main pathways of photosynthesis, referred to as C_3 and C_4 which refers to the number of carbon atoms fixed as sugar for plants to metabolise. In addition, there is the pathway called CAM (Crassulacean Acid Metabolism) (Brown and Brown 2011:82; Ben-David and Flaherty 2012:315). The CAM pathway primarily occurs in succulents and since these plants are rare in subarctic settings, this photosynthetic pathway will not be elaborated on here. Identification of these different pathways in plants is possible due to the carbon fractionation process that happens during photosynthesis where the ratio of ^{13}C and ^{12}C varies between the different pathways, resulting in different $\delta^{13}C$ values (Brown and Brown 2011:83). Plants build their sugars when fixing carbon dioxide, C_3 plants utilise building blocks that are three carbon atoms long, while the C_4 plants use four carbon atom long building blocks (Brown and Brown 2011; Fernandes and Jaouen 2017). Consequently, in all plants there is an enrichment of atmospheric carbon dioxide during the photosynthesis, however how the plants synthesise the carbon glucose in the Rubisco process is what differentiates the different pathways.

The C_3 photosynthesis pathway is more discriminatory of ^{13}C in the fixation process of carbon dioxide as the lighter ^{12}C isotopes (atoms) are converted to glucose more rapidly than ^{13}C. The C_4 pathway stores carbon dioxide in the plant cells before converting almost all the carbon dioxide into glucose which in turn leads to the C_4 plants having more enriched $\delta^{13}C$ values (Brown and Brown 2011:83; **Figure 6**). Atmospheric carbon has a value of around −8‰ relative to the standard VPBD, however after the fractionation process of carbon in the C_3 plants $\delta^{13}C$ values are depleted with values of −24‰ to −36‰. Meanwhile the C_4 plants have $\delta^{13}C$ values of approximately −12.5‰ (Brown and Brown 2011:82,83; Ben-David and Flaherty 2012:315; **Figure 6**). The $\delta^{13}C$ values of these different plants will be reflected in the animals feeding on them when following the different levels in the food chain (Brown and Brown 2011:82,83). Consequently, this is useful because it can determine what sorts of plants animals or humans have been eating, and with that one can determine where they have been eating. The C_3 photosynthesis pathway is the dominating food crop in northern Europe in prehistoric times, but plants like maize, sugarcane and millet which belongs to the C_4

plants could have been imported in Nordic regions (Guiry et al. 2016:1-2). It has been shown in studies that people living in northern Europe with a fully terrestrial C_3 diet had $\delta^{13}C$ values around −20‰ to −21‰ measured from bone collagen (Liden and Nelson 1994). This differentiation can lead archaeologists to interpret when certain food groups were introduced (Liden and Nelson 1994; Brown and Brown 2011:80-87; Bogaard and Outram 2013; Nehlich 2015; Outram and Bogaard 2019:53).

Further, the canopy effect is a gradient depletion of $\delta^{13}C$ values in forests and heavily grown areas (Van der Merwe and Medina 1991; Ben-David and Flaherty 2012). This is a by-product of photosynthesis in low light environments like a forest floor, or other such environments. Since plants rely on sunlight to conduct photosynthesis, hence also the fractionation process of ^{13}C, low light environments like forest floors will then affect this process (Bonafini et al. 2013:3926,3927). The gradient which can occur due to CO_2 recycling and decomposing leaves on the forest floor in such environments causes $\delta^{13}C$ values closer to the forest floor to be more negative, with measured values as low as −37‰ in the Amazon rain forest (Van der Merwe and Medina 1991; Bonafini et al. 2013). Consequently, such values would affect the food chain, resulting in isotopic differences between the animals feeding in closed forests and open grazed landscapes, and as such, habitat it is an important factor to consider in interpreting isotopic data.

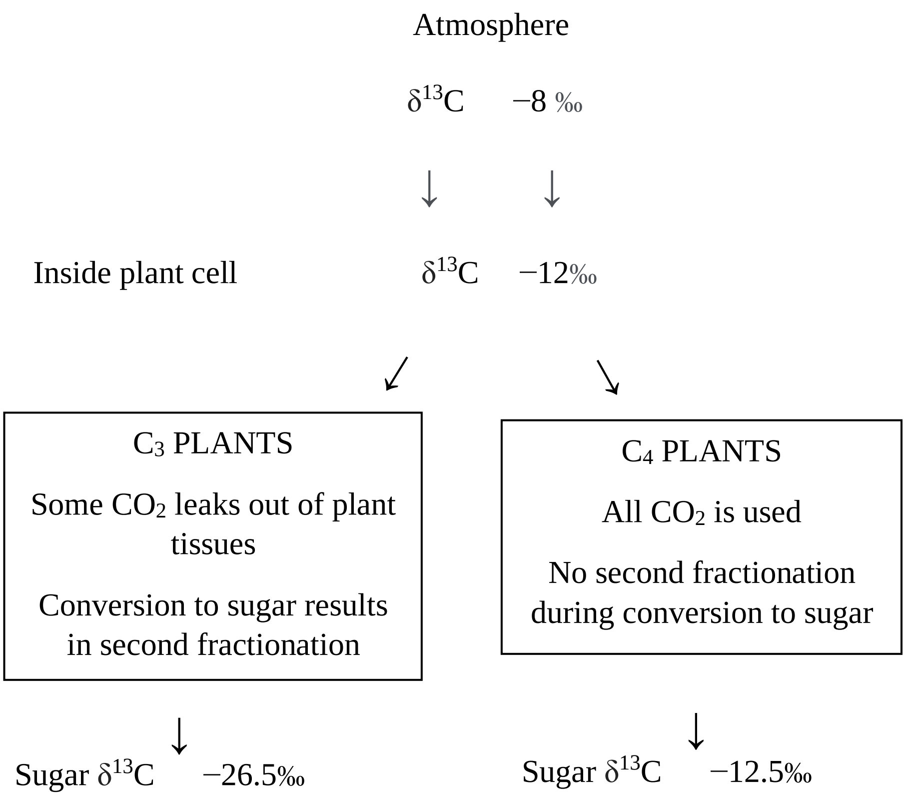

Figure 6: Adapted from Figure 6.1 in Terence A. Brown and Keri Brown (2011:82), schematic explanation of photosynthesis in plants and their fractionation of ^{13}C.

Carbon is indicative of the protein derivative of the diet (Balasse et al. 2001:238). The marine food web displays more enriched $\delta^{13}C$ values compared to the terrestrial diet of C_3 plants (Outram and Bogaard 2019:53). This is because the incorporation of carbon in the photosynthesis of marine plants like plankton and algae does not occur with atmospheric carbon dioxide but dissolved bicarbonate that gets photosynthesised, which is more enriched in ^{13}C than atmospheric carbon dioxide, causing the marine $\delta^{13}C$ values to be around −16‰ (Brown and Brown 2011:83,84). This will then be reflected in the consumer that have fish/marine protein in the diet. Hence, ^{13}C isotopes can in addition be used in the identification of marine vs terrestrial diets. ^{15}N is often used in conjunction with ^{13}C to avoid confusion of values of marine vs C_4 diets. This is known as the principle of equifinality, as an example; C_4 and marine diets will appear similar in their isotope values, if only the $\delta\,^{13}C$ values were to be considered. In combining both ^{15}N and ^{13}C to avoid this principle, since the $\delta^{15}N$ values can indicate of marine protein has been part of the diet or if the values are due to a C_4 diet. Consequently, this indicates the importance of combining multiple isotopes in interpreting diet (Brown and Brown 2011:84. 85).

4.4 Nitrogen isotopes:

Nitrogen has two isotopes ^{14}N and ^{15}N, ^{14}N is abundant in the biosphere. The reference standard is atmospheric air, also called "AIR" (Brown and Brown 2011:80,81; **Table 3**). The process of nitrogen fractionation can be explained in the form of a process called denitrification. The food web includes plants, herbivores, carnivores and omnivores and where you are on this scale can be reflected by $\delta^{15}N$ values (Outram and Bogaard 2019:53). The food chain in the ocean is longer and consists of more components than the terrestrial food chain. Similarly, nitrification is greater in the ocean vs terrestrial soils which leads to more enriched $\delta^{15}N$ values in ocean species (Brown and Brown 2011:84,85). In archaeology the ^{15}N isotope has most commonly been used as an indicator of trophic level in dietary studies, the reason for this being that there exist successive levels of so-called enrichments values up the food chain. The enrichment value between different steps in the food chain is approx. 3-5‰ for each step (Nehlich 2015:6). In addition, $\delta^{15}N$ value enrichment in the food chain includes nursing animals who will be a trophic level above their mothers values (Fornander et al. 2008:284). Different factors like penned animals, living in their own dung can also lead to enrichment of their $\delta^{15}N$ values, also known as pigsty latrine environment (Guiry et al. 2021:5; Laszlo Bartosiewicz, personal communication April 2021).

As an example of the utilisation of $\delta^{13}C$ and $\delta^{15}N$, Robson et al. (2016) investigated the differences between oceanic fish and freshwater fish to demonstrate the enrichment of ^{15}N in ocean environments. Studies measuring $\delta^{13}C$ values and $\delta^{15}N$ values in fish can further elaborate on the different food sources utilised by humans and animals regarding marine/freshwater input in the diet vs terrestrial. Studies like the one conducted by Robson et al. (2016) investigating $\delta^{15}N$ and $\delta^{13}C$ values in fish bone has developed the understanding of these different dietary inputs and with that one can further elaborate on human and animal resource use, trade and mobility **(Table 4)**.

Habitat	**$\delta^{13}C$**	**$\delta^{15}N$**	**Taxon**
Freshwater/brackish water	−24.2 to −19.3	6.5 to 12.7	general
Marine/brackish water	−14.9 to −9.4	6.5 to 12.7	general
Marine	−13.4 ± 0.9	10.9 ± 1.1	spurdog
Freshwater/brackish water	−25.6 ± 0.4	5.4 ± 0.4	tench

Table 4: Isotopic values relative to Mesolithic and Neolithic northern Europe. Different δ values between freshwater and marine/ocean fish, values adapted from Robson et al. (2016).

4.5 Sulphur isotopes:

In recent years the use of sulphur isotopic values has been on the rise in mobility studies in the field of archaeology. However, this is still a developing science. The element of sulphur is abundant in the ocean, hydrosphere and in the lithosphere, and the standard is called Vienna Canyon Diablo Troilite (VCDT) (Nehlich 2015:3). The element of sulphur has four stable isotopes ^{32}S, ^{33}S, ^{34}S and ^{36}S, the main source of sulphur isotopes on earth are differences in geologies vis-a-vies rock minerals, soil, oceanic and estuarine sulphur (Nehlich 2015). Sulphur is taken up by an organism in two different ways, sulphur from local bedrock is taken up in plants that animals eat and is distributed up the food chain that way. Alternatively, due to sea spray effect which entails oceanic sulphur affecting the grazing area of the animals. $\delta^{34}S$ values vary up to 40‰ between the deep-sea food web and estuarine environments. The reason for this variance is the uptake of sulphates in deep sea environments and sulphides in estuarine environments (Ben-David and Flaherty 2012:316). ^{34}S is enriched in marine environments relative to the more abundant ^{32}S the fractionation of heavier and lighter isotopes and can be used to trace distance to the coast (Nehlich 2015). Oceanic sulphur is generally stable at around +20.3‰ and +21‰, while freshwater, estuarine environments, rain and snow derived $\delta^{34}S$ values most commonly have values between 0 to +10‰ (Claypool et al. 1980; Trust and Fry 1992:1105-1106; Zazzo et al. 2011:2370-2372; Nehlich 2015; **Table 5**). Terrestrial geological $\delta^{34}S$ values are usually represented by lower $\delta^{34}S$ values between 0 to 5‰, respectively, it is commonly believed that plants are depleted 1.5‰ in $\delta^{34}S$ values compared to their sulphur source due to fractionation between soil and or atmospheric sulphur $\delta^{34}S$ values to plant $\delta^{34}S$ values (Sayle et al. 2013; Nehlich 2015). These differences between $\delta^{34}S$ in the different environments can be utilised as a dietary niche indicator.

Lower values of ^{34}S are often indicative of a sulphur source in the diet that derives from depleted bedrock sulphur and terrestrial sources, while higher values usually above a threshold of +14‰ are usually indicative of sulphur deriving from more oceanic sulphur or sea spray affected areas (Zazzo et al. 2011; Nehlich 2015:10; Hamilton et al. 2019; **Figure 7**). The sea spray effect occurs when oceanic sulphur is carried inland by the wind and affect the grazing areas of animals (Zazzo et al. 2011; Sayle et al. 2013; Nehlich 2015; Hamilton et al. 2019). The distance for sea spray effect may vary from a few kilometres inland to entire islands depending on wind speed and prevailing conditions. Thus, it is commonly set a threshold of <50 km inland for sea spray effect, however landmass and hydraulic factors are critical factors to consider when evaluating $\delta^{34}S$ values (Nehlich 2015). Similarly, it is possible for terrestrial sulphur to mimic the higher values of sea spray, in these cases evaporitic rocks causes the geological sulphur to have quite high values, which again will be reflected in the archaeological samples from these areas (Warren 2010; Nehlich 2015). Due to this isotopic variance of $\delta^{34}S$ values in the environment, local geological values should always be considered for a given study area, which gives more precise reference to analysed samples. The utilisation of $\delta^{34}S$ values has been shown to be useful in tracing animal and human mobility, in addition to an indicator of differences between aquatic or terrestrial dietary components when compared with $\delta^{13}C$ and $\delta^{15}N$ values (Trust and Fry 1992; Zazzo et al. 2011; Nehlich 2015).

Sulphate source:	δ^{34}S:
European granite	− 4 to +9‰
Oceanic	+ 20.3‰
Freshwater	0 ‰ to + 10 ‰

Table 5: Sulphate sources with δ‰ values (Nehlich 2015).

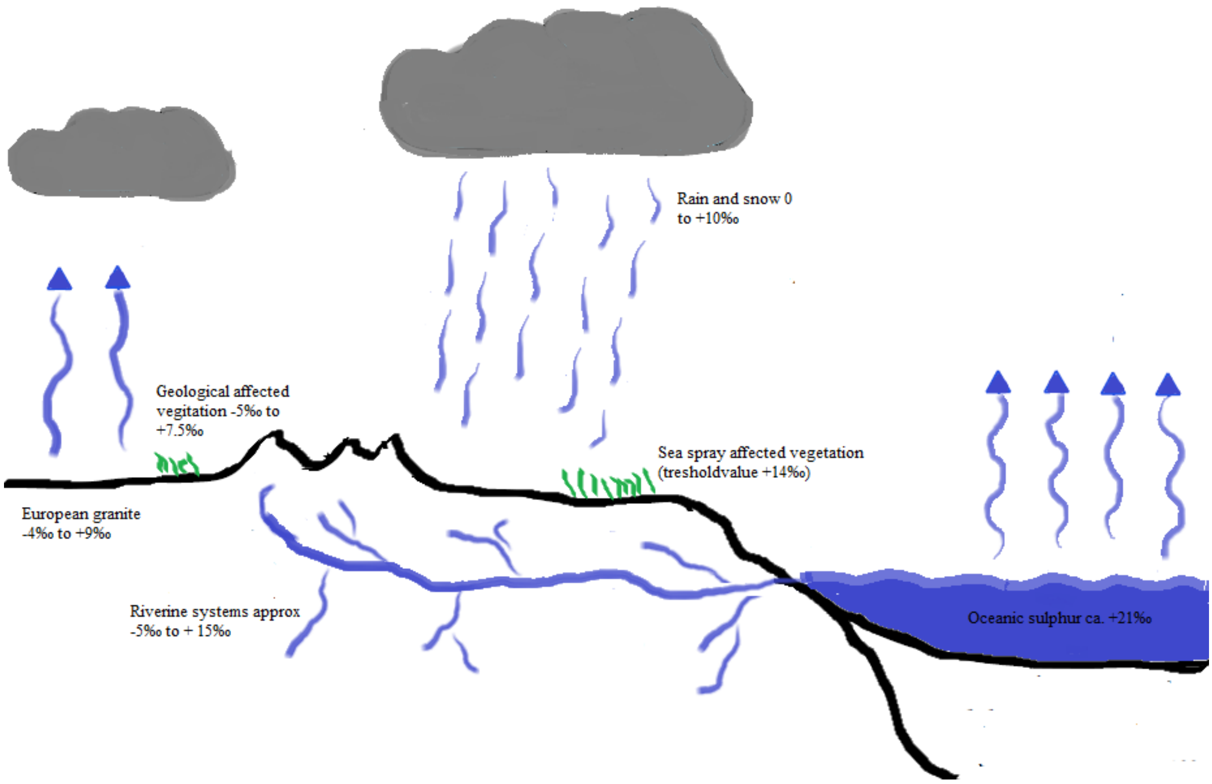

Figure 7: Sulphur cycling in the environment, info and adaptation from Figure 2 in Nehlich (2015), values calculated and changed to be as relevant as possible for the site in question for this thesis (Birka).

4.6 Strontium isotopes:

The isotope most commonly used for mobility studies is strontium. Strontium has four naturally occurring stable isotopes: ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr. However, ^{87}Sr derives from the radiogenic element rubidium-87 (^{87}Rb), which steadily decays into the stable isotope of ^{87}Sr (Balasse et al. 2002:919; Bentley 2006). To compare archaeological strontium values a local baseline for the site or region in question must be established, also known as the bioavailable strontium or baseline (Bentley 2006; Price et al. 2018). Bioavailable strontium usually occurs from weathering rocks and minerals into the local geology. For instance, different minerals within the same rock can contribute to different $^{87/86}$Sr ratios which again unevenly gives different ratios to the bioavailable strontium (Bentley 2006:141,142). However, there are several factors that determines strontium distributed in the biosphere and it is due to how it forms in geological systems. In addition, rivers can carry a mixture of geological deposits, altering the strontium signatures compared to the local geology of a site (Lahtinen et al. 2021). This must be kept in mind when analysing and interpreting $^{87/86}Sr$ values in archaeological samples. For more information see Bentley (2006) and Åberg and Wickman (1987). The geological factors are often investigated to connect archaeological humans or animals to a geographic area or migration questions (Bentley 2006:136; Blank et al. 2018).

In establishing a local baseline for an area, one can track mobility of animals or humans by plotting their strontium values against the baseline. There is no general consensus to what should be used as baseline, however some rodents are often used as these are considered to not move around a lot in the landscape (Blank et al. 2018; Price et al. 2018). While collagen from the bone can be used for ^{15}N and ^{13}C, strontium is determined from the inorganic part of teeth as tooth enamel is much less susceptible to diagenesis making it the most reliable source to measure for these isotopes (Blank et al. 2018; Outram and Bogaard 2019:68). Strontium taken up through diet has similar properties to calcium (Ca) and is usually substituted for Ca in the carbonate hydroxyapatite (CHA), apatite is the main mineral in which dentine and dental enamel are composed (Lahtinen et al. 2021:2). Strontium is passed through the trophic network from bedrock to the biosphere then to the consumer be that either human or animal with little biological isotope fractionation (Balasse et al. 2002; Blank et al. 2018:5; Lahtinen et al. 2021:4).

4.7 Case studies utilising isotope analysis:

Linderholm et al. (2008) and Linderholm and Kjellström (2011) conducted a multi-isotopic analysis of the human population at Birka and Sigtuna, the latter is the Medieval successor town to Birka. Their studies investigated differences in diet between different burial types. They conducted isotope analysis utilising $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values from animals to cross-reference the burial values. For further information on the human burial results see the respective studies. The results of the analysed animals from Birka had $\delta^{13}C$ values in accordance with a terrestrial C_3 diet. However, the $\delta^{15}N$ values were quite high (~8.0‰) and a standard deviation (s.d) of 3.8‰ indicating a rather varied diet (Linderholm et al. 2008; Linderholm and Kjellström 2011). A s.d. of 0.3‰ is generally regarded as a homogenous diet according to Lovell et al. (1986). Consequently, from the Birka material only two $\delta^{34}S$ values were obtained, one from a horse with $\delta^{34}S$ values of −2.7 ± 0.7‰, and a pig with a 0.0‰ both values fall within the range of the local geologic $\delta^{34}S$ values of European granite (Nehlich 2015). Further, the local human $\delta^{34}S$ values from Sigtuna averaged 7.1 ± 2.4‰, and Birka averaged 5.2 ± 2.5‰, in line with the local geology of European granite, and the animal values (Linderholm et al. 2008; Linderholm and Kjellström 2011; **Table 5**).

Sayle et al. (2013) investigated mobility and food niches of animals at Lake Mývatn, Iceland. The study utilised 129 samples from animal bone collagen. The ^{34}S isotopes allows for a detection of an offset (differentiating values) between different dietary niches, like marine with a $\delta^{34}S$ mean of +15.6 ± 1.5‰, terrestrial with a of mean +5.6 ± 2.8‰ and freshwater have a mean of – 2.7 ± 1.4‰ (Sayle et al. 2013: 532). The offset of ^{34}S compared to the more commonly used ^{13}C and ^{15}N, can add more information of diet and mobility (Sayle et al. 2013). This can be used as an indicator of where an animal derived their food source from, compared to the values of the site in question (Sayle et al. 2013; Sayle et al. 2019). The domesticated animals from this study displayed $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values with averages ranging between −21.3 ± 0.4‰, +3.0 ± 1.3‰, 5.6 ± 2.8‰, respectively. The $\delta^{13}C$ values were indicative of a C_3 diet which was unsurprising for this Arctic location. The $\delta^{34}S$ values on the other hand were indicative of the animals deriving from different locations, this is due to the variance between the animals isotopic signatures indicating different sulphur sources in their diet (Sayle et al. 2013:537,538). Further this study took ^{14}C samples of pigs, which revealed much older dates than the site in question, the reason for this was interpreted as the pigs eating freshwater fish. The freshwater fish gave a reservoir effect on the pig values making them appear older. Consequently, an FRE effect were found on modern fish samples from Mývatn (Sayle et al. 2013:540; Sayle et al. 2016). This study gave a good indication of the value of utilising $\delta^{34}S$ values compared to $\delta^{13}C$ and $\delta^{15}N$ values to trace mobility of animals, and dietary niches.

The study conducted by Blank et al. (2018) has measured strontium values from mainly the western part of Sweden. The results were indicative of varied geological values with generally lower values closer to 0.713 in the western part, while higher values up to 0.743 were measured for the eastern and northern parts of Sweden (Blank et al. 2018). Motala 180km southwest of Birka is a good example of how areas of different bedrock can vary substantially in one region. The western part of Motala has Cambro-Silurian sedimentary terrain with values from 0.714 to 0.728, while in the northern part of Motala there are

Precambrian sediments with values from 0.731-0.743. The bioavailable range in Sweden is usually quite high due to the ancient geology, which gives rise to quite high values of strontium isotopic ratios, indicating that strontium is suitable as a proxy for mobility studies in this region (Risberg et al. 2002:446-447; Price et al. 2014; Price et al. 2018:32).

The study by Price et al. (2018) conducted strontium measurements for Birka and Mälaren. This was done to establish a baseline for the region. This study investigated the human population at Birka, and the presence of non-local and local individuals buried at Birka. The baseline proxy for Birka were measured from rodents, the results from these measurements were 0.7267 ± 0.0012 (Blank et al. 2018; Price et al. 2018). For the larger Mälaren region the values range between 0.7225 and 0.7316, the bioavailable baseline established at 0.723-0.733 (Blank et al. 2018; Price et al. 2018:31). The conclusion was that strontium were a valuable tool in tracing mobility, and that some of the measured individuals were in fact non-local.

Chapter 5. Methods

5.1 The sampling process:

The archaeological material utilised for this thesis is from the 2015-2016 in the Harbour excavation area of Birka. After extensive communication with Sven Kalmring and Johnny Karlson, the decision was made to request access to this material, on the basis of both quality and quantity and the relative dating of the different layers. The layers were dated with relative dating according to Callmer's (1977) bead chronology **(Table 1)**, the material had a good spread in time, which suited the research question for this thesis. A permit was provided by the University of Stockholm (24.08.2020) for destructive analysis in the form of collagen/enamel extraction for isotope analysis and in addition osteological investigation of the material to get a better understanding of the animal bone material as a whole.

The sampling of the material was conducted at the University of Stockholm in September and October of 2020. A technique of a randomised stratified sampling was utilised to cover the layers in a sequential dynamic order. The agreed number of samples for destructive analysis for extraction of collagen for isotope analysis were a total of 45 samples, including both bone and teeth from the permitted material. The original plan was to analyse 15 cattle, 15 pig and 15 sheep, giving an overall clear division of each taxonomic group. Further, the strategy was to get a good spread of samples from the different layers L17, L23, L30, L32, L35 and L37. However, after osteological analysis done by M. Wadstål in guidance from Laszlo Bartosiewicz (a zooarchaeologist at the University of Stockholm) it became clear that the material did not provide a satisfying number of sheep bones, and an overrepresentation of cattle bones for the 15 cattle, 15 pig and 15 sheep division to be sufficiently upheld.

Subsequently, a decision was made to change the taxonomic division to 21 cattle, 14 pigs and 10 sheep. The laboratory chosen for the light stable isotope analysis is the only one that currently is capable of conducting sequential NCS (nitrogen, carbon and sulphur) analysis on small sample sizes (~ 1.5mg bone collagen). Consequently, the destruction of the material is considerably less, than with a lab that requires two separate samples to obtain the same results. In addition, Dr Kerry Sayle, who works at the Scottish Universities Environmental Research Centre (SUERC) in East Kilbride, developed the above technique and she offered to assist with the interpretation of the results. For the described method see Sayle et al. (2019).

The depositional environment has the possibility to cause diagenetic processes in bone, causing the preservation of collagen to be altered or poor (Mays et al. 2013:8). Since prescreening for carbon content in the bones were not possible, it was determined to utilise a selective randomized sampling strategy of bone sampling. Consequently, the topmost layers (L1-16) were excluded due to poor preservation, scrambling of layers due to ploughing of the soil and risking non-sufficient extraction of collagen from the bones (Sven Kalmring, personal communication October 2020). Due to the project limit of 45 samples, it was deemed best to aim for the layers that would give the best depth of information as well as the best chances of good collagen preservation. In addition, at this point in time (September-October 2020) we did not have access to the excavation report or layers overview to underline the evaluation of the different layers. Hence, in the end the division between bone and teeth were set to nine teeth and 36 bones, giving the total 45 sample limit. Further, determining how many samples that should be divided between the NCS analysis, $^{87/86}$Sr and which four samples to conduct ^{14}C radiocarbon dating on, lastly dividing the five teeth samples for strontium between the species and layers for the most feasible results.

The aim was to sample as many similar bones ergo dense bones as possible for the most coherent results, as different types of bones have different turnover rates of collagen (Bentley 2006:162). However, it was not always possible to get the same type of bone for the entirety of the sample division between the taxonomic groups (cattle, pig, sheep). The focus was aimed at sampling from cortical bones, which are compact long bones that contain more collagen than trabecular bones, such as ribs (Mays et al. 2013:10; Jones and Mulville 2018; Elise Neumann, personal communication September 2020). The teeth for strontium samples were divided so that three teeth from each taxonomic group were extracted, the second molar (M2) was chosen each time. The reason for this was so that the animals analysed would be of approximately the same age (adult/ subadult).

When the process of selecting bones suitable for analysis were complete, the bones were sampled using a Dremmel 8100 handheld drill and a Proxxon MICROMOT 40E handheld drill. Each bone selected for sampling were photographed and measured before sampling. The work area for the extraction process was covered with aluminium foil, with an extra sheet to catch the bone dust from the drilling. The reason for using aluminium foil was that it is easy to change out in between samples and aluminium does not react with organic substances, so it would not contaminate the bone samples (David Wright, personal communication September 2020). The first step was to determine where to sample on the bone and in what way i.e. oblong or V-shaped. This decision was made based on the preservation, what type of bone and if the bone was whole or fragmented. The aim was to ensure as minimal damage as possible, while managing to extract ~ 1g of sampling material, as required by the SUERC laboratory.

The second step was attempting to avoid the marrow hole in the middle of the bone as this can contain dirt and could contaminate the sample (Kendall et al. 2018; Elise Neumann, personal communication September 2020). The selected sample area was drilled lightly using a milling cutter bit to remove the surface area of the bone to minimise contamination. When the surface area was ready, a diamond drill bit was used to bore into the bone to extract a sample. The drill was wiped with 95% fine spirit to clean it after every sample and then left to air-dry, the drill bits were also cleaned in 95% spirit between samples and air-dried to avoid cross-over contamination as much as possible. Gloves, an industrial grade face mask and safety goggles were always used during the sampling process. The gloves were changed between each sample and the goggles were also wiped with 95% spirit to clean off bone dust for every sample. The samples were weighed on a scale and then transferred into Eppendorf plastic coring tubes, labelled and the weight was recorded in an Excel-spreadsheet.

The M2 molar from cattle was taken from partly or fully preserved mandibles, the aim was to extract the tooth without damaging the mandible or having to cut it in half. This was achieved for 2/3 of the extractions. Consequently, the same tactic was utilised for pig and sheep, the pig mandibles were successfully extracted on all three attempts. The sheep mandibles were fragmented or fragile so the aim here was to extract the molar (M2) without causing destruction to the molar itself. The molars were then weighted and wrapped in aluminium foil for transport.

LabNo	**ContextID**	**SampleID**	**Bone/tooth**
GUsi10299	Cattle L 17 PQ 16	Sample 1	Radius
GUsi10300	Cattle L 23/I PQ 16	Sample 2	Radius
GUsi10301	Cattle 23/II PQ 15	Sample 3	MT
GUsi10302	Cattle L 23/III PQ 8	Sample 4	MT
GUsi10303	Cattle 23/IV PQ 16	Sample 6	MT
GUsi10304	Cattle L 30 PQ 6	Sample 7	MT
GUsi10305	Cattle L 36 PQ 13	Sample 9	MT
GUsi10306	Cattle L 37 PQ 14	Sample 10	Radius
GUsi10307	Cattle L 35 PQ 1	Sample 11	Tibia
GUsi10308	Cattle 23/IV PQ 16	Sample 12	Tibia
GUsi10309	Cattle L 30 PQ 2	Sample 13	MT
GUsi10310	Cattle 37 PQ 14	Sample 14	Femur
GUsi10311	Pig L 17 PQ 16	Sample 16	Calcaneus
GUsi10312	Pig L 23/I PQ 15	Sample 17	Femur
GUsi10313	Pig L 23/II PQ15	Sample 18	Humerus
GUsi10314	Pig L 23/III PQ 8	Sample 19	Tibia
GUsi10315	Pig L23/V PQ 14	Sample 20	Tibia
GUsi10316	Pig L 23/IV PQ 14	Sample 21	Calcaneus
GUsi10317	Pig L 30 PQ 16	Sample 22	Tibia

GUsi10318	Pig L 35 PQ 5	Sample 23	Tibia
GUsi10319	Pig L 37 PQ 14	Sample 24	Femur
GUsi10320	Pig L 32 PQ 14	Sample 25	Humerus
GUsi10321	Sheep L 17 PQ 16	Sample 26	Tibia
GUsi10322	Sheep L 23/I PQ 16	Sample 27	Humerus
GUsi10323	Sheep L 23/IV PQ 16	Sample 28	Tibia
GUsi10324	Sheep 23/V PQ 14	Sample 29	MT
GUsi10325	Sheep L 30 PQ 6	Sample 30	MT
GUsi10326	Sheep L 32 PQ 14	Sample 31	Ulna
GUsi10327	M2 Cattle L17 PQ 16	Sample 32	M2
GUsi10328	M2 Cattle L 23/III PQ 8	Sample 33	M2
GUsi10329	M2 Cattle L 37 PQ 14	Sample 34	M2
GUsi10330	M2 Pig L 23/I PQ 16	Sample 35	M2
GUsi10331	M2 Pig L 23/III PQ 8	Sample 36	M2
GUsi10332	M2 Pig L 37 PQ 14	Sample 37	M2
GUsi10333	M2 Sheep L 23/III PQ 14	Sample 38	M2
GUsi10334	M2 Sheep L 23/IV PQ 10	Sample 39	M2
GUsi10335	M2 Sheep L 23/II PQ 16	Sample 40	M2
GUsi10336	Cattle L 23/III PQ 14	Sample 41	MT
GUsi10337	Sheep L 37 PQ 14	Sample 43	MT
GUsi10338	Pig L 23/III PQ 14	Sample 44	Radius
GUsi10339	Cattle L 17 PQ 5	Sample 45	MC
GU56884	Cattle L 23/V PQ 14	Sample 5	MC
GU56885	Cattle L 32 PQ 14	Sample 8	MC
GU56886	Cattle L 35 PQ 1	Sample 15	Radius
GU56887	Cattle L 23/III PQ 8	Sample 42	Tibia

Table 6: Sample overview of lab numbers, taxonomic groups and bone type. MT = metatarsal, MC = meta carpal. Gray shading indicates the samples chosen for radiocarbon dating.

5.2 Sample pre-treatment:

Lab codes GU56884 to GU56887 were given to the samples that underwent ^{14}C-dating including NCS analysis **(Table 6)**. While GUsi10299-GUsi10339 lab codes were given to the samples measured solely for NCS (in which 20% of the samples ran duplicate) and strontium analyses. The division of the 45 samples were four for ^{14}C-dating, five for $^{87/86}$Sr analysis, and 41 for NCS analysis.

The SUERC radiocarbon laboratory practices a modified version of the Longin (1971) to extract collagen from archaeological bone samples, for the entire description of the method see Dunbar et al. (2016). The following description were repeated for all the bone samples. The bone sample (~ 1g) was added to a solution of 100 mL 1M HC1 for approximately 24 hours, this was to dissolve the apatite. The acid was then removed/decanted, and the sample was washed with ultrapure water. Then 100 mL of ultrapure water was added to the solution, and the sample was further warmed on a hotplate at 80°C for approximately 4 hours. The collagen solution was then filtered with a GF/A (fine particle retention filter), then dried down to <20 mL and transferred to a glass vial. The final step entailed freeze drying to obtain the collagen powder from the sample solution (Dunbar et al. 2016:2-4). Freeze drying is a method utilised for the avoidance of preferential volatilization, which is what happens when changes in the molecules containing the lighter isotopes occur from for example evaporation or diffusion which would cause inaccurate isotope values (Ben-David and Flaherty 2012:314,315).

The tooth enamel pre-treatment involved placing the sample in 100 mL of ultrapure water and a sonic bath for removal of tissue. The tooth sample was then rinsed and a Dremel multitool was utilised to remove the crown, and the internal dentine was removed with a dissecting needle (Dunbar et al. 2016:5). The crown was then placed in a 10M NaOH (sodium hydroxide) solution and heated to 80°C. Dentine was scraped from the enamel and the sample was rinsed in 0.5M HCl to remove all the NaOH, and the final step is to rinse it again in the ultrapure water. The enamel was then dried in an oven and transferred to a glass vial (Dunbar et al. 2016:5; Kerry Sayle, personal communication April 2021).

5.3 NCS isotopic analysis:

The collagen samples (~ 1.2 - 1.5mg) were combusted in the presence of oxygen in a single reactor containing tungstic oxide and copper wires at 1020°C to produce N_2 (nitrogen), CO_2 (carbon dioxide) and SO_2 (sulphur dioxide). A magnesium perchlorate trap was used to eliminate water produced during the combustion process, and the gases were separated in a GC (gas chronography) column heated between 70°C and 240°C (Dunbar et al. 2016:13-14; Sayle et al. 2019:1259-1261). Helium was used as a carrier gas throughout the procedure. N_2, CO_2, and SO_2 entered the mass spectrometer via an open split arrangement within the ConfloIV and were analysed against their corresponding reference gases (Dunbar et al. 2016; Sayle et al. 2019:1259-1261). Stable nitrogen ($\delta^{15}N$), carbon ($\delta^{13}C$), and sulphur ($\delta^{34}S$) isotopic compositions were determined on a Delta V Advantage continuous-flow isotope ratio mass spectrometer (CF-IRMS) coupled via a ConfloIV to an IsoLink elemental analyser (Thermo Scientific, Bremen) (Dunbar et al. 2016:13-14). This method follows the criteria and method as described in Sayle et al. (2019) and Dunbar et al. (2016).

For reference to the standards applied at the SUERC laboratory see: https://doi.org/10.6084/m9.figshare.16857901.v1

5.4 Radiocarbon dating:

For the SUERC radiocarbon dating, the samples were weighed into a quartz insert and then placed into a cleaned quartz combustion tube containing copper oxide to provide oxygen for the reaction to occur. Silver foil is utilised to not introduce impurities of gaseous form (Dunbar et al. 2016:9). The SUERC laboratory in-house quality assurance involves primary and secondary known-age standards, and a tertiary in-house standard referenced directly to the oxalic acid primary standard (SRM-4990C) (Dunbar et al. 2016:9). At the SUERC radiocarbon laboratory there are two different AMS instruments for radiocarbon dating, one is National Electrostatics Corporation (NEC) 5MV tandem accelerator mass spectrometer and a 250 kV single-stage accelerator mass spectrometer (SSAMS) (Dunbar et al. 2016:9-11). The NEC utilises two sources and the SSAMS utilises one. When analysing the samples are usually divided into 13 groups with 10 samples in each group. Then each group has three standards used, oxalic acid II primary standard, humic acid is the secondary standard, the last one is often a barley mash, and then seven unknowns (Dunbar et al. 2016:12,13). The process follows the protocols and methods set up in Dunbar et al (2016).

5.5 Strontium analysis:

The $^{87/86}Sr$ analysis was conducted in a Class 100 clean room laboratory which is a controlled environment for particles, airborne particles and humidity (Kerry Sayle, personal communication April 2021). The samples were first weighed into a Teflon beaker and then dissolved in 2x distilled dilute HC1, then a known amount of ^{84}Sr reference spike was added to calculate the strontium concentrations in the samples (Dunbar et al. 2016:6). The dissolved samples were then dried before column chemistry. The method of TrisKem Sr spec resin column were utilised, the method is described in Pin and Bassin (1992). Then the next step was drying of the samples prior to loading them into a VG sector 54-30 thermal ionisation mass spectrometer (TIMS). The samples were then loaded onto single RE filaments similar to the ones described in Birck (1986).

5.6 Statistics:

Isotopic data can be represented in a comparable manner by plotting the values into statistical programs like R. Bayesian ellipses are part of the SIBER (stable isotope Bayesian ellipses in R) package, which utilises Monte Carlo simulations to measure the probability of different outcomes from a set of data (Newsome et al. 2007; Jackson et al. 2011). Isotopic data can be presented as biplots, where for instance isotope values of animals portray the animals niche width, the values are represented in δ space, which means the isotopic values are delineated by their isotopic composition (Newsome et al. 2007; Jackson et al. 2011). Clusters of isotopic data with similar δ values can then be detected. This type of scatter plots gives the user an easier way to sort through and compare data. Consequently, two main niches can be separated, trophic niche and isotope niche, these different niches are represented on the different axes (x,y) in a plot (scatterplot). Further, the axes can be described as the scenopoetic axes and the bionomic axes, whereas the latter describes the trophic component of niches, and the former describes environmental components of niches (Jackson et al. 2011:595). As an example, $\delta^{15}N$ values increase with each step in the food chain, and hence represents the bionomic axes. Whereas the values of for instance $\delta^{34}S$ values vary with environment and geographical regions, represents the scenopoetic axes. There is an assumption when running these models, that is that the data is representative of a multivariate normal distribution (Jackson et al. 2011:597)

For this thesis, the results were firstly divided in $\delta^{13}C$ values vs $\delta^{15}N$ values, $\delta^{15}N$ values vs $\delta^{34}S$ values, $\delta^{13}C$ vs $\delta^{34}S$ values. The layers sampled were then divided into six groups whereas some groups with fewer samples were put together to make the data more lucid. The three taxonomic groups sampled were given the numbers 1,2,3 (1 = cattle, 2 = pig, 3 = sheep) and were plotted as community, these are represented as ellipses in the scatterplots **(Figure 8 and 9).** This was done to compare $\delta^{13}C$ vs $\delta^{15}N$ values, and $\delta^{34}S$ vs $\delta^{15}N$ values across the layers. The next division was between three pooled groups of isotopic input, separated in $\delta^{34}S$ sea spray, $\delta^{34}S$ terrestrial sulphur source and enriched $\delta^{15}N$ input, the groups were representing the three animal groups, and the communities were representing the three different inputs of food sources **(Figure 10 and 11).** The final product was the creation of the scatterplots the taxonomic groups, this simulation was to compare the isotopic values between the animal groups. Thus, for this simulation the groups were the different animals (1,2,3) and the layers were the community component (1-6) still divided into six, grouping the layers with fewer samples to make the data more lucid and readable **(Figure 13).**

Boxplots were used to represent the quantitative data from the isotopic dataset. Boxplots were utilised because they are good visualisation tool for different niche widths of the data (Hu 2020). Firstly, the isotope values were separated by isotopic composition ($\delta^{15}N$, $\delta^{13}C$ and $\delta^{34}S$), secondly by their taxonomic group, cattle, pig, and sheep, one boxplot for each isotopic composition were modelled to visualise the different input of the isotopic values between the taxonomic groups **(Figure 12).**

OxCal was utilised for calibrating the ^{14}C dates to account for inconsistencies in the ^{14}C as mentioned in Chapter 4, the calibration curve IntCal20 Northern Hemisphere Radiocarbon Age were utilised for calibrating the ^{14}C results conducted by the SUERC Radiocarbon Laboratory (Reimer et al. 2020). All the results were given in BP (Before present 1950 = 0) and must be calibrated to calendar dates for CE. The calibration was done at 2 σ (95.4%) certainty level.

Chapter 6. Results

6.1 NCS isotopic results:

All of the samples had sufficient collagen yield above 1%, and C/N were within the acceptable range ratio of 2.9-3.6 for good quality bone preservation described in DeNiro (1985). Sulphur concentration was within the acceptable quality criteria of 0.15-0.35%, and the N/S and C/S ratios were also within the acceptable range set out in Nehlich and Richards (2009). For all results see **appendices**. None of the samples had to be excluded from the research of this thesis (Fornander et al. 2008; Nehlich 2015; Roberts et al. 2018; Sayle et al. 2019; **appendices**).

The Monte Carlo simulation of these isotopic data indicates a spread in the isotopic values, also within the different layers **(Figure 8 and 9).** L23 has the most overall variance in δ values leaning towards enrichment in $\delta^{15}N$ and $\delta^{34}S$ values, L23 was also the biggest anthropogenic layer as defined in the excavation. L30 and L32 pools slightly into two groups for their $\delta^{13}C$ values, with one group slightly enriched in $\delta^{13}C$. L35, L36 and L37 fall into three different groups $\delta^{13}C$ values slightly enriched, enriched $\delta^{15}N$ values and intermediate values.

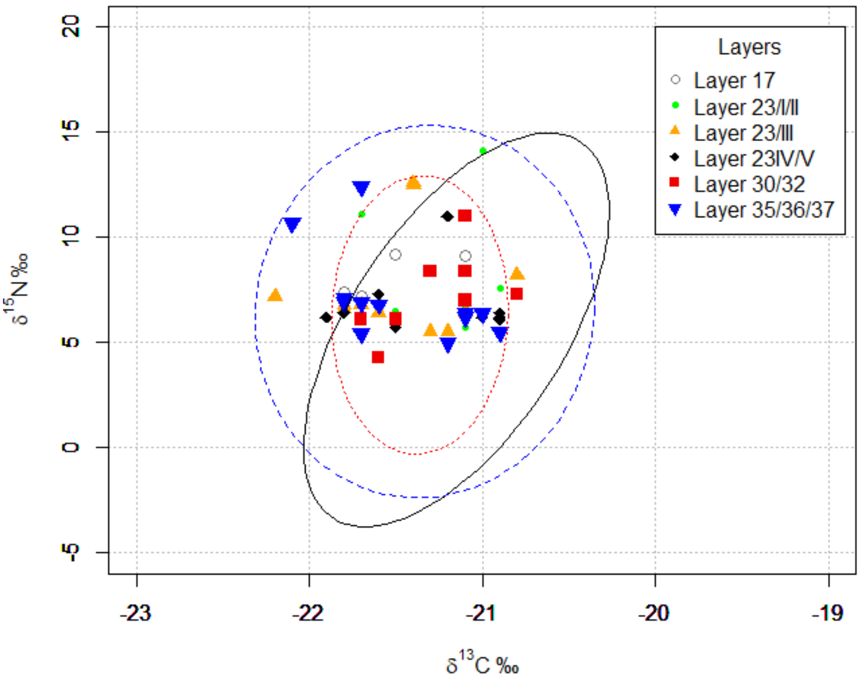

Figure 8: scatterplot ellipses $\delta^{13}C$ vs $\delta^{15}N$, red ellipse simulates the distrubution of sheep values based on the assayed data, black ellipse represents cattle and blue dotted ellipse represents pigs. Calculated from the entirety of values, see **appendices** for a total overview of samples

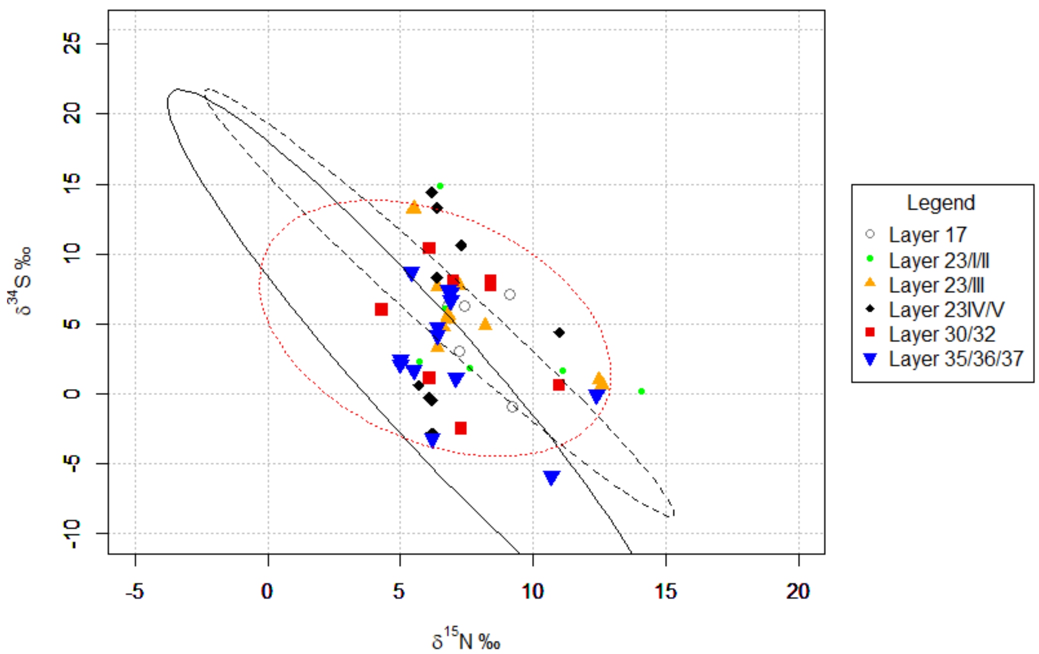

Figure 9: scatterplot ellipses $\delta^{34}S$ vs $\delta^{15}N$, red ellipse simulates the distrubution of sheep values based on the assayed data, black ellipse represents cattle and blue dotted ellipse represents pigs. Calculated from the entirety of values, see **appendices** for a total overview of samples.

L17	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Mean	8.0	−21.5	4.4
S.d	1.1	0.3	3.3
Min	6.8	−21.8	−0.9
Max	9.2	−21.1	7.1

L23	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Mean	7.5	−21.4	5.3
S.d	2.4	0.4	5.1
Min	5.5	−22.2	−2.8
Max	14.1	−20.8	14.9

L30	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Mean	7.2	−21.4	7.1
S.d	1.1	0.3	3.5
Min	6.1	−21.7	1.1
Max	8.4	−21.1	10.4

L32	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Mean	7.6	−21.2	1.4
S.d	3.4	0.4	4.3
Min	4.3	−21.6	−2.5
Max	11	−20.8	6.0

L35	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Mean	8.2	−21.4	3.0
S.d	3.7	0.4	3.9
Min	5.5	−21.7	−0.1
Max	12.4	−20.9	7.4

L37	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Mean	6.7	−21.4	2.1
S.d	1.7	0.4	4.4
Min	5.0	−22.1	−5.9
Max	10.7	−21.0	7.2

Table 7: Average $\delta^{15}N$, $\delta^{13}C$ and $\delta^{34}S$ values of the layers, layer 36 was not averaged.

		$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$
Cattle	mean	6.4	−21.4	4.9
	s.d	0.7	0.3	3.2
	min	4.3	−21.8	−3.2
	max	7.4	−20.9	10.6
Pig	mean	9.1	−21.5	5.4
	s.d	2.8	0.4	6.6
	min	5.5	−22.2	−5.9
	max	14.1	−21.0	14.9
Sheep	mean	7.1	−21.1	2.8
	s.d	1.7	0.2	4.0
	min	5.0	−21.5	−2.8
	max	11.0	−20.8	10.4

Table 8: Average (mean) $\delta^{15}N$, $\delta^{13}C$ and $\delta^{34}S$ values of the taxonomic groups.

Carbon results: The cattle $\delta^{13}C$ values range from −21.8‰ to −20.9‰ with a mean of −21.4 ± 0.3‰, respectively. The $\delta^{13}C$ values for the pigs vary between −22.2‰ to −21.0‰ and have a mean of −21.5 ± 0.4‰. The sheep $\delta^{13}C$ values range between −21.5‰ to −20.8‰ and have a mean of −21.1 ± 0.2‰, respectively **(Table 7 and 8).** The standard deviation for cattle and sheep is indicative of a narrow dietary niche with respect to carbon, as a s.d. below 0.3‰ is considered a homogenous deviation (Lovell et al. 1986). The pig has on average a s.d. of 0.4‰, which indicates a slightly more varied dietary niche.

Nitrogen results: The average $\delta^{15}N$ values for cattle range between 4.3‰ and 7.4‰ and have a mean of 6.4 ± 0.7‰. The pig values range from 5.5‰ and 14.1‰ and have a mean of 9.1 ± 2.8‰, respectively. The sheep values range from 5.0‰ to 11.0‰ with a mean of 7.1 ± 1.7‰, respectively. Six pig samples and one sheep (GUsi10312, GUsi10318, GUsi10320, GUsi1030-32, GUsi10334) **(appendices)**, have $\delta^{15}N$ values of above 10.6‰ compared to the rest of the samples who have a $\delta^{15}N$ value of below 8.0‰, respectively. These results are indicative of variance in the dietary input and these higher $\delta^{15}N$ values of nitrogen are due to either input of marine protein in the diet, nursing animals or wallowing in dung, as mentioned in chapter 4.

Sulphur results: Cattle $\delta^{34}S$ values range from −3.2‰ and 10.6‰ and have a mean of 4.9 ± 3.2‰, respectively. The pig values range from −5.9‰ and 14.9‰ and have a mean of 5.4 ± 6.6 ‰, respectively. The sheep values range from −2.8‰ and 10.4‰ and have a mean of 2.8

± 4.0‰, respectively. These results are indicative of a great variance in the sulphur component of the diet, as indicated by the greater than 0.3‰ s.d. **(Table 7 and 8).**

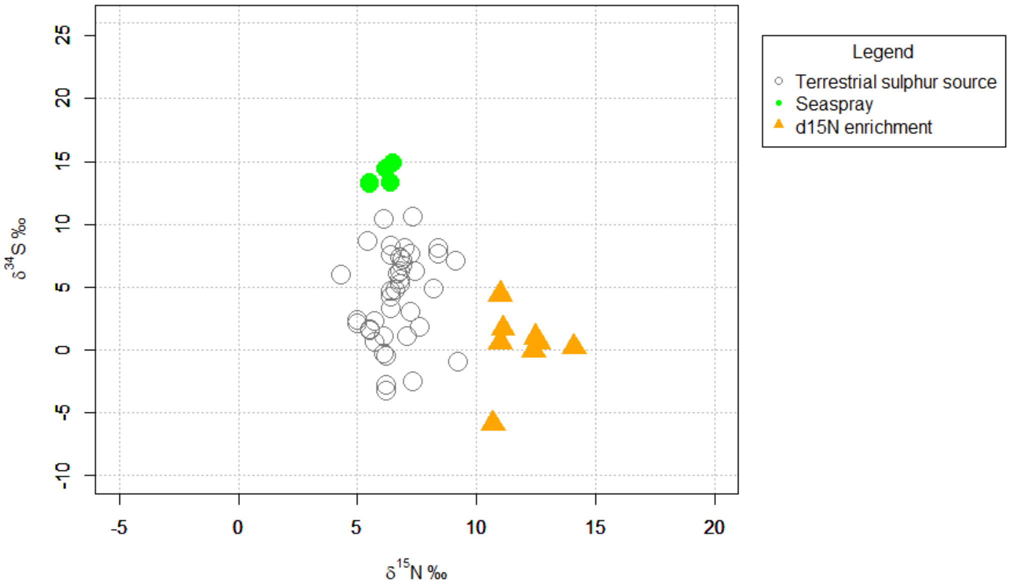

Figure 10: Scatterplot of differentiating dietary inputs values for the different inputs calculated from Nehlich (2015), explanation of the thresholds is provided in Chapter 4 of this thesis.

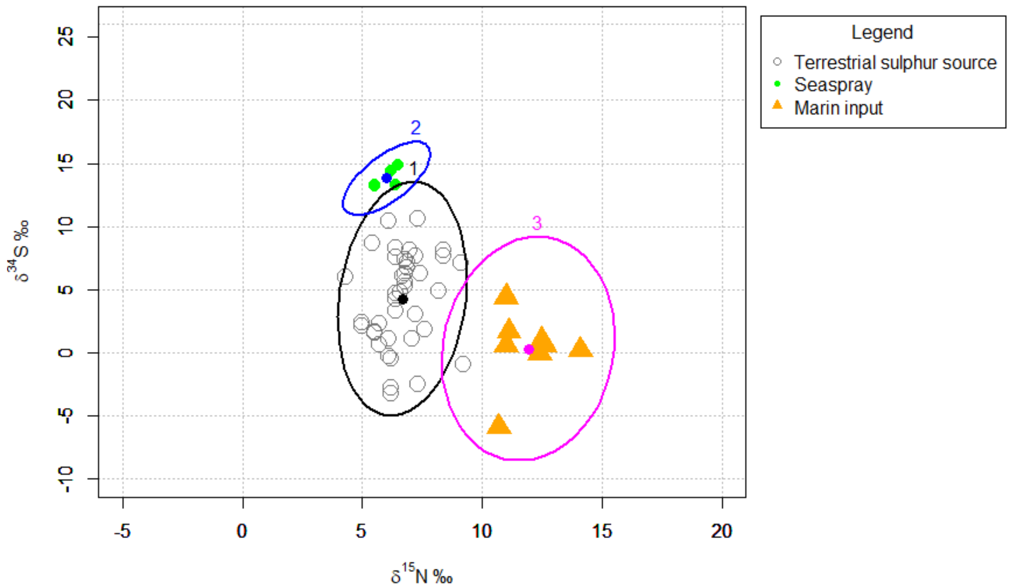

Figure 11: Food sources (above) with ellipses representing the three different inputs, sea spray, terrestrial sulphur source and δ^{15}N enrichment

In considering the relationship between δ^{34}S values and δ^{15}N values, a three-part division can be deduced. The δ^{34}S values and the input of the δ^{15}N values can be pooled in three different categories: δ^{34}S values possibly affected by sea spray, δ^{34}S values closer to the geological values of the study area (European granite ergo terrestrial source sulphur) and marine/freshwater or other enrichment input of δ^{15}N values. This is an indication of different dietary input of ^{34}S and ^{15}N for the animals, which means that they either derive from different areas or were fed different diets **(Figure 10 and 11).**

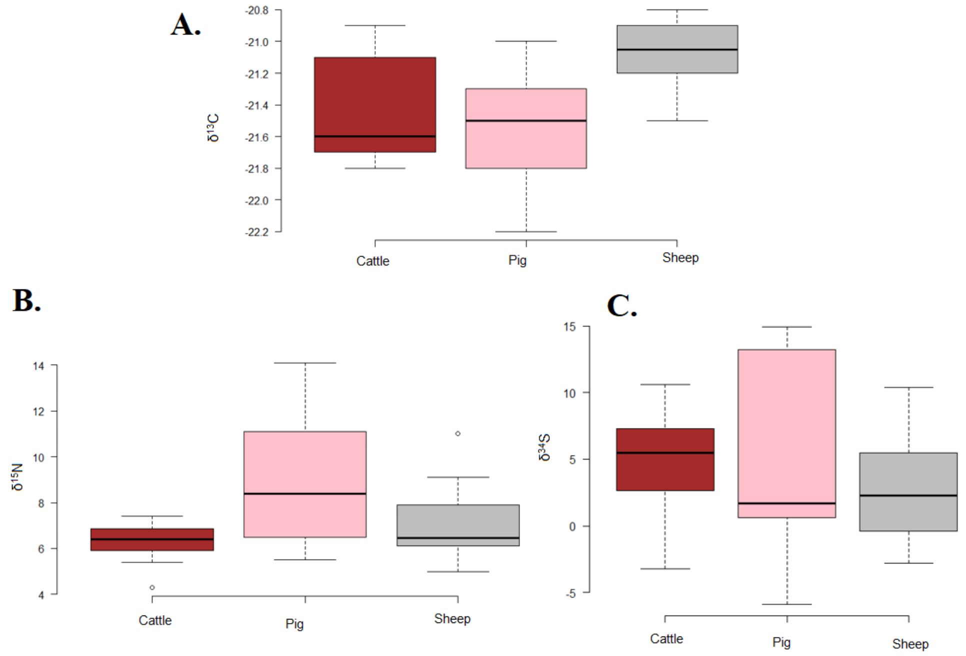

Figure 12: Boxplots (above) for niche widths of the taxonomic groups, The black line is the median, the whiskers are the standard deviation (s.d.) the little circle is an outlier value (Hu 2020).

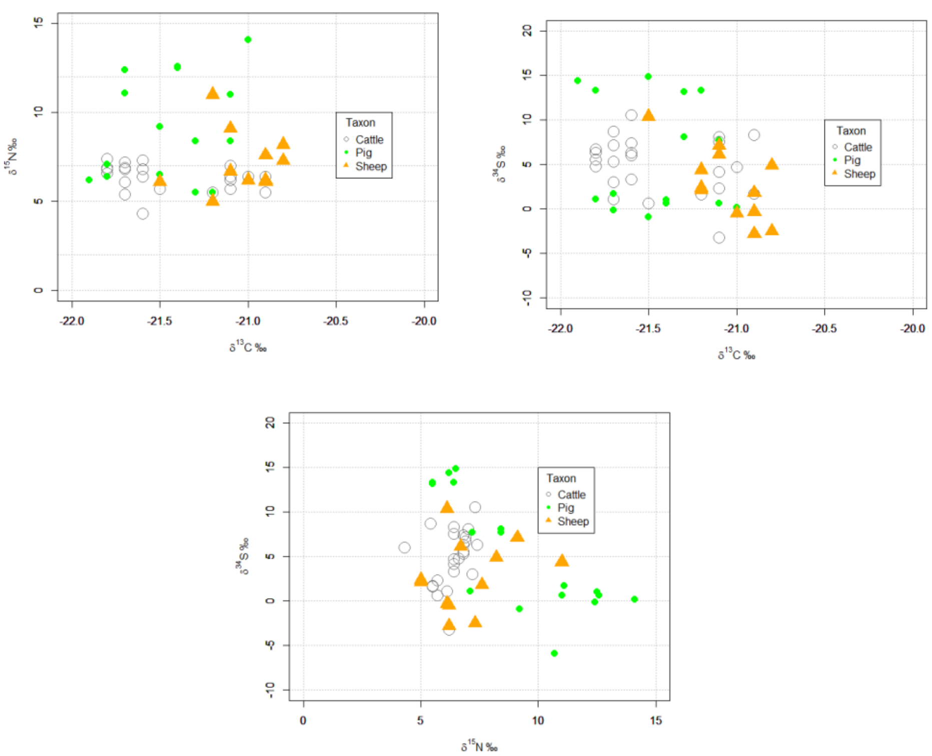

Figure 13: Combined scatterplots of $\delta^{13}C$ vs $\delta^{15}N$ values, $\delta^{13}C$ vs $\delta^{34}S$ values and $\delta^{15}N$ and $\delta^{34}S$ values.

The scatterplots and boxplots of the $\delta^{13}C$ vs $\delta^{15}N$ values indicate that cattle seem to split in two different groups **(Figure 12 and 13)**. The sheep $\delta^{13}C$ values are for the most part comparable with the cattle values with just slightly enriched $\delta^{13}C$ values. The presence of pigs with enriched $\delta^{15}N$ values < 10‰, and the two sheep samples with the same enrichment, could indicate the presence of goats in the material and that these animals had a different dietary niche for the $\delta^{15}N$ component of their diets (Arnold et al. 2018:8). The scatterplot of $\delta^{13}C$ vs $\delta^{34}S$ values indicates that there is enrichment of the $\delta^{34}S$ values for within the taxonomic group of pigs. The same trend can be detected in the $\delta^{15}N$ vs $\delta^{34}S$ values where there is enrichment of $\delta^{15}N$ values for pigs and sheep, and some enrichment of $\delta^{34}S$ values. The boxplots indicates that pigs are the taxonomic group with the most isotopic variance in their diet. Further, the small variance indicated by the boxplots for cattle in $\delta^{15}N$ indicates that the pigs were eating a varied diet for their protein source. The sheep $\delta^{13}C$ values indicates that they had little variance in their C_3 intake but more so than the cattle, which due to the possibility of goats being present in the sheep material. The boxplot $\delta^{13}C$ values indicates more variance for the cattle, which is further explained in the scatterplots as the cattle samples seem to split in two different groups for their $\delta^{13}C$ values.

6.2 Radiocarbon dating results:

To calibrate the four radiocarbon dates the program OxCal was utilised with the function of R_Date to combine the values in a multiplot, the calibration curve of IntCal20 northern hemisphere calibration curve was utilised (Dunbar et al. 2016; Dury et al. 2018; Reimer 2020; Reimer et al. 2020; **Figure 14 and Table 9, SUERC radiocarbon certificates in appendices**). The radiocarbon ages indicate an earlier settlement and import of animals to the town of Birka prior to 730CE. The radiocarbon dates indicate that the accumulation of the anthropogenic waste in the harbour was therefore earlier than the relative dating of Callmer's (1977) bead chronology suggests.

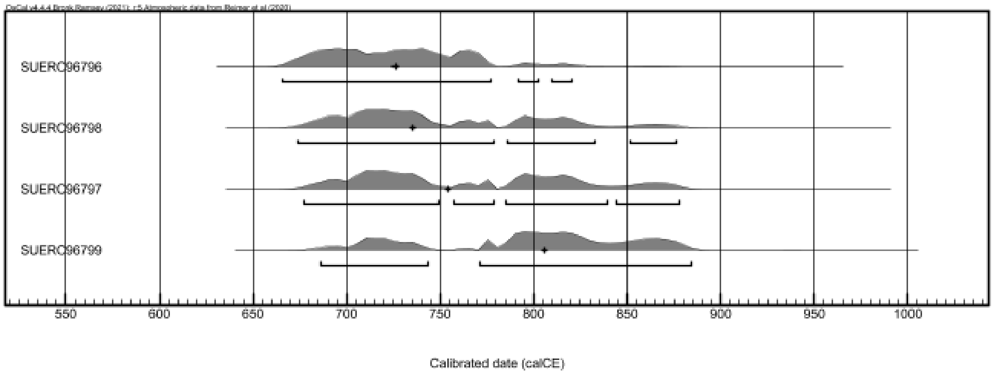

Figure 14: SUERC radiocarbon results (above), calibrated with IntCal20 atmospheric calibration curve in OxCal (Reimer 2020; Reimer et al. 2020).

#Sample	$\delta^{13}C$ (‰)	uncalibrated age BP	calibrated age 2σ	Median (95.4%)	Layer
SUERC-96796 (GU56884)	−21.6	1275 ± 26	665-820 CE	726 CE	Layer 23/V
SUERC-96797 (GU56885)	−21.6	1245 ± 26	677-878 CE	754 CE	Layer 32
SUERC-96798 (GU56886)	−20.9	1252 ± 26	674-876 CE	735CE	Layer 35
SUERC-96799 (GU56887)	−21.1	1228 ± 26	686-884 CE	806 CE	Layer 23/III

Table 9: Radiocarbon results for Birka, calibrated utilising IntCal20 calibration curve (Reimer et al. 2020).

6.3 Strontium results:

The five samples chosen for strontium $^{87/86}Sr$ analysis had values ranging between 0.7274 and 0.7418 **(Table 10 and 11)**. The s.d. for the strontium values are indicative of a homogenous diet in regards to the strontium intake from the environment (Bentley 2006:158). However, the variance in the $^{87/86}Sr$ values are indicative of different geological origin of the animals (Dury et al. 2018; **Table 10 and 11**).

Sample Name	$^{87/86}Sr$	% Std Error	2σ abs error	Sr conc(ppm)	2σ (%)
GUsi10327	0.738787	0.0012	0.000018	232.3	0.36
GUsi10328	0.741783	0.0014	0.000021	258.7	0.41
GUsi10329	0.739416	0.0013	0.000019	158.2	0.22
GUsi10330	0.729232	0.0012	0.000018	113.6	0.21
GUsi10332	0.727375	0.0012	0.000017	138.0	0.26

Table 10: SUERC laboratory $^{87/86}Sr$ results ppm=parts per million

Sample Name	$^{87/86}$Sr	δ^{15}N (‰)	δ^{13}C (‰)	δ^{34}S (‰)	Taxon
GUsi10327	0.7388	7.4	−21.8	6.3	Cattle
GUsi10328	0.7418	6.8	−21.7	5.3	Cattle
GUsi10329	0.7394	6.2	−21.1	−3.2	Cattle
GUsi10330	0.7292	11.1	−21.7	1.7	Pig
GUsi10332	0.7274	10.7	−22.1	−5.9	Pig

Table 11: $^{87/86}$Sr, δ^{15}N, δ^{13}C, δ^{34}S values.

6.4 Data interpretation:

The results of the isotope analyses are indicative of a varying origin of the three animal groups which suggests a broad reaching socioeconomic network of the animal provisioning economy for Birka, in the Viking Age. $^{87/86}$Sr results suggests that the cattle and pigs derived from different geological areas. The $^{87/86}$Sr baseline for Birka and the Mälaren region has previously been set between 0.723-0.733 (Price et al. 2018:31). The cattle samples (GUsi10327, GUsi10328 and GUsi10329) $^{87/86}$Sr values range closer to north Motala while the pig's (GUsi10330 and GUsi10332) values are closer in range to the general Mälaren baseline (Blank et al. 2018; Price et al. 2018; **Figure 15, Table 11 and 12**). Assuming the assayed strontium values accurately reflect the geologic source at the time of enamel formation, the cattle found in Birka would in this scenario have been imported from at least 180km away. Interestingly, the $^{87/86}$Sr values from cattle also ranges closer to values commonly found in Finland **(Figure 15 and Table 12)**. Previous research from Birka has elucidated to the fact that Finnish grave goods and material has been found at Birka (Linderholm et al. 2008; Price et al. 2018). Further, a third explanation would be that these cattle derived from northern Sweden as $^{87/86}$Sr values there usually are >0.73 (Blank et al. 2018:7). The representation of the entirety of the cattle skeleton at Birka, could indicate that the animals were transported there as a walking commodity and slaughtered on site (Zeder 1988; Wigh 2001).

Birka	Mälaren Baseline	Motala North	Motala Baseline	Sweden	Finland
0.7267-0.7256	0.723-0.7233	0.731-0.743	0.714-0.728	0.711 to < 0.735	0.7293
Rodents	Fauna	Soil	Fauna and soil	Geological survey	Geological survey

Table 12: Baselines for $^{87/86}$Sr values from different parts of Sweden and Finland, baseline info taken from Blank et al. (2018); Price et al. (2018).

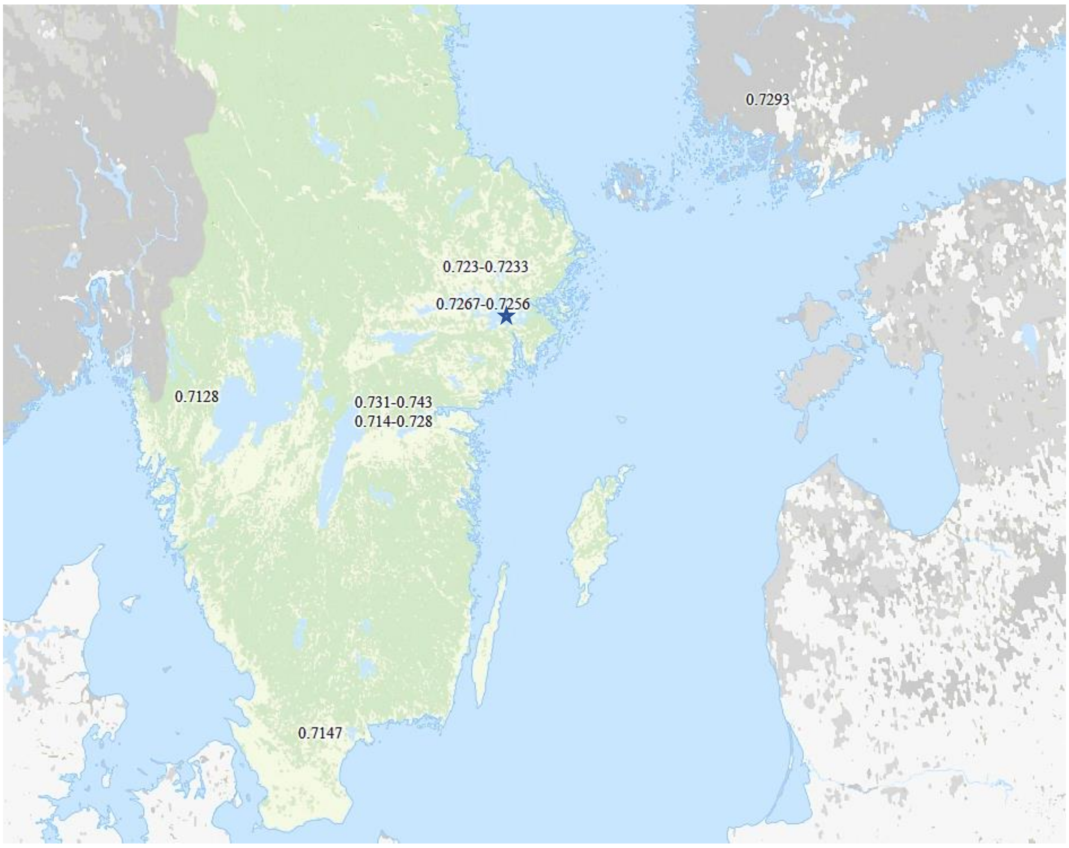

Figure 15: Strontium baselines information adapted from Price et al. (2014); Blank et al. (2018); Boethius and Ahlström (2018); Price et al. (2018). Star marks the position of Birka.

The results of the $\delta^{13}C$ values are indicative of a terrestrial diet of C_3 plants, which was common in the northern hemisphere in the Viking Age. The study by Liden and Nelson (1994:3-7) of the prehistoric Baltic concluded people with a C_3 terrestrial diet would have $\delta^{13}C$ values between −20‰ and −21‰. The three taxonomic groups fall within this threshold. The cattle pools in two different groups for their $\delta^{13}C$ values which is usual for different grazing areas reflected in their $\delta^{13}C$ values (**Figure 12;** Kerry Sayle, personal communication May 2021). The sheep $\delta^{13}C$ values are for the most part comparable with the cattle, with some enrichment of their $\delta^{13}C$ values. This enrichment in sheep could be due to their feeding habits, cattle are grazers while sheep will supplement their diet with vegetation like forbs giving them a more diverse range of C_3 plants (Balasse et al. 2002:952; Arnold et al. 2018). The $\delta^{13}C$ values give a good indicator that both sheep and cattle in general were grazing/feeding on a terrestrial C_3 diet and that C_4 plants were not imported, or at least not utilised for animal fodder at this point in time.

Five pigs (GUsi10312, GUsi10318, GUsi10320, GUsi10330, GUsi10332) and one sheep (GUsi10334) exhibits higher $\delta^{15}N$ values than the expected terrestrial protein source of <10‰, which can be indicative of four separate scenarios (Sayle et al. 2013). The first scenario is that the animals were wallowing in their own dung which is associated with being penned, causing a latrine environment (Laszlo. Bartosiewicz, personal communication April 2021). Second, the animals could have been consuming a higher source of protein such as freshwater or marine fish, which have higher δ^{15}N values. It is also a possibility that sample (GUsi10334) is a goat, given that goats are more likely to have eaten fish scraps as they are mixed feeders compared to sheep (Arnold et al. 2018:8). Finally, the higher δ^{15}N values could be that the animals were weaning and represent a trophic level shift above their mothers (Linderholm et al. 2008). All four scenarios would cause these enriched δ^{15}N values.

The study by Linderholm et al. (2008) also identified pigs with higher δ^{15}N values from Birka. These values were interpreted to be due to nursing/weaning animals. However, the osteological investigation conducted by Wadstål (2021) on the bone material from the 2015/2016 Harbour excavation showed that most of the pigs were subadult. Hence, the above explanation of penned animals in latrine environments or freshwater/marine fish scraps is a more viable hypothesis for the higher δ^{15}N values observed in these samples. Attesting the higher δ^{15}N values for these pigs to the consumption of fish scraps would fall in line with the isotopic values for freshwater/brackish water fish analysed in the study by Robson et al. (2016) with δ^{15}N values 5.4 ± 0.4‰, and the consumer would be 3-5‰ above that due to the enrichment of ^{15}N up the food chain as mentioned earlier **(Table 5).** Further, freshwater/brackish water fish would coincide with the water around Birka during this time, as it consisted of brackish water concluded by Risberg et al. (2002). Interestingly, the δ^{34}S values for these enriched δ^{15}N samples follow the trend of enriched δ^{15}N values and depleted δ^{34}S, which indicates that these animals were not affected by sea spray or raised close to the coast. The anatomical representation of the entirety of pig skeletons, identified by Wadstål (2021) further suggests that some pigs could have been kept locally at Birka.

The local geology at Birka and Mälaren mostly consists of granite and gneisses. The δ^{34}S values for this bedrock fall between −4‰ to +9‰, and with the depletion compared to the sulphur source due to fractionation of 1.5‰ these, values should be around −5‰ to +7.5‰ for the consumer (Sayle et al. 2013:533; Blank et al. 2018; Price et al. 2018). The majority of the samples have δ^{34}S values that fall within this threshold of δ^{34}S values for European granite. However, δ^{34}S values for four of the pigs (GUsi10313, GUsi10314, GUsi10315, GUsi10316) were enriched with values between 13.2‰ and 14.9‰. Further, there was no evidence of a marine influence of these samples, as their δ^{15}N values are between 5.5‰ and 6.5‰. Consequently, a viable conclusion is then that these higher δ^{34}S values are due to a sea spray effect. Alternatively, these pigs could have come from a geologic area with higher $\delta^{34}S$ values than the European granite (Nehlich 2015). Consequently, these $\delta^{34}S$ values indicate that these animals were not local to Birka and probably raised closer to the coast, or in geological areas with higher $\delta^{34}S$ values than the European granite of the Mälaren region before ending up in Birka.

The pigs (GUsi10330 and GUsi10332) with $^{87/86}Sr$ values closer to the Mälaren baseline have enriched $\delta^{15}N$ values, and depleted $\delta^{34}S$ values. These pigs should have derived from the same geographical region on the basis of their $^{87/86}Sr$ values, however their $\delta^{34}S$ values are quite different, which indicates they originated from an area with a different $\delta^{34}S$ value. Consequently, they were both eating fish, or penned in latrine environments which can attest to pigs kept locally at Birka, as concluded by Wigh (2001). On the other hand, s previously mentioned some pigs have $\delta^{15}N$ values more in line with terrestrial values <10‰, but some also have enriched $\delta^{34}S$ values, which can attest to either sea spray effect and coastal residence or origin from a geographical area with higher $\delta^{34}S$ values in the geology (Sayle et al. 2013; Nehlich 2015). This elucidates a vast reaching import of animals from different regions to this central place.

The radiocarbon dating conducted for this thesis yielded dates significantly older than the previously set of dates for the excavated layers was previously determined by the relative bead chronology by Callmer (1977). The deviation between the relative and the absolute dates could be accounted for based on a couple of different reasons, such as scrambling of layers, diagenesis, the lack of base a marine curve for calibration. Reservoir effect could also possibly be affecting the dates conducted for this thesis. The study by Sayle et al (2013) utilised radiocarbon dating conducted on pig bones, which resulted in a falsely older age because the isotopic analysis of $\delta^{15}N$, $\delta^{13}C$ and $\delta^{34}S$ concluded that these pigs had been eating fish scraps from a lake with a proven FRE. Because the $\delta^{34}S$ and $\delta^{15}N$ values were enriched it was confirmed that these pigs had been eating fish, which again demonstrated a reservoir effect on these animals. The reservoir effect made the animals from the Sayle (2013) study appear older than the site in question.

However, the radiocarbon dating conducted for this thesis was measured on cattle, to avoid reservoir effects since cattle are not omnivores and would not feed on freshwater or marine protein. The $\delta^{13}C$ values for the cattle samples falls within a terrestrial diet of C_3 diet, with values ranging from −20.9‰ to −21.6‰. There is also no evidence for post-burial interlayer mixing of archaeological deposits by rodents or other disturbance agents (Kalmring et al 2021). Further, some of the previously generated absolute dates from the 2015/2016 excavation coincides better with the older dates from this research, where wood from preserved jetty posts were radiocarbon dated. These samples were taken from L11 and trench 2 the LuS samples were from jetty posts driven through L11 down to L30 (marine clay). The Ua samples were from timer/wickerwork possibly reused found in trench 2 (Kalmring et al. 2021:65,85; **Figures 16,17 and Table 13**). Therefore, the dates conducted for this thesis seem to indicate earlier activities of urban character than previously believed. This is attested to by Ambrosiani (2013:16) when discussing Birka’s development and connections which would have been at work before the historically set date of the Viking Age in 793 CE. Consequently, further research and more ^{14}C dates would be useful in understanding the scope of Birka as a central place.

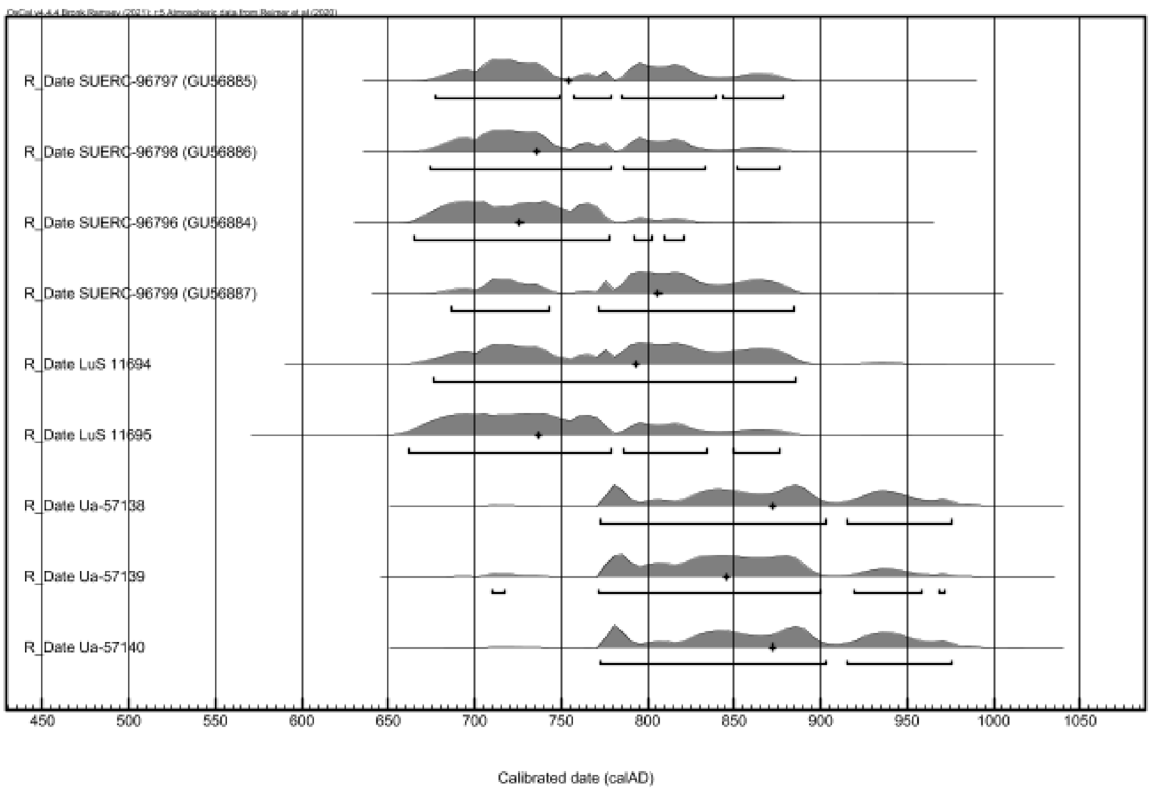

Figure 16: Comparison OxCal model with absolute dating (radiocarbon) from the Harbour excavation 2015/2016 samples dates and LuS and Ua Lab ID (jetty posts and wickerwork) taken from Kalmring et al. (2021) compared to the SUERC radiocarbon ages. Calibrated with IntCal20 (Reimer et al. 2020).

#Sample ID	Median	Material
SUERC-96796 (GU56884)	726 CE	bone
SUERC-96797 (GU56885)	754 CE	bone
SUERC-96798 (GU56886)	735 CE	bone
SUERC-96799 (GU56887)	806 CE	bone
LuS 11694	793 CE	jetty post
LuS 11695	736 CE	jetty post
Ua-57138	872 CE	wickerwork
Ua-57139	845 CE	wickerwork
Ua-57140	872 CE	wickerwork

Table 13: All radiocarbon dates conducted on the 2015/2016 Harbour material, LuS and Ua (L11) sample ID’s taken from Kalmring et al. (2021). Calibrated to the OxCal IntCal20 calibration curve (Reimer et al. 2020).

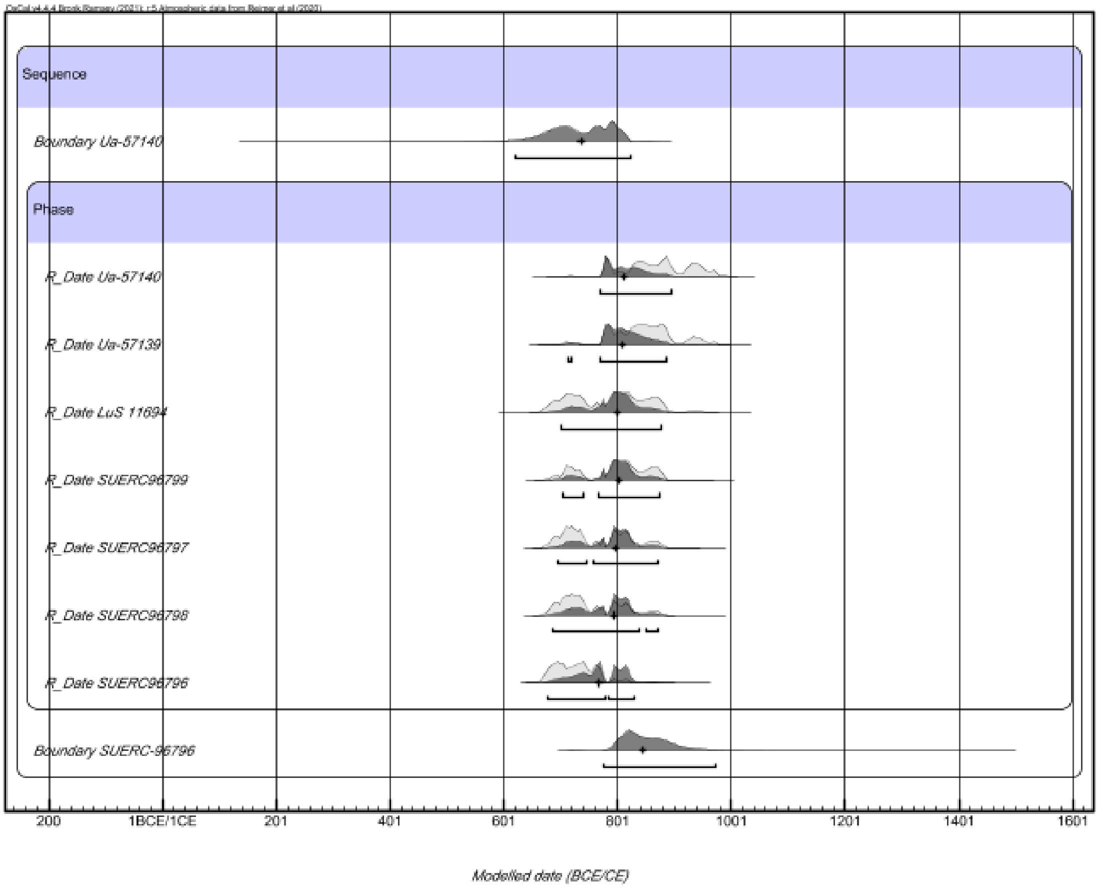

Figure 17: Deposition model, Ua and LuS sample ID’s taken from Kalmring et al. (2021), calibrated with IntCal20 in OxCal (Reimer et al. 2020)

Chapter 7. Discussion and Conclusion

7.1 Discussion:

The island of Birka was too small to sustain the population and would have been dependent on its subsistence networks for food provisioning. The plant species identified by Risberg et al (2002) indicated that not a lot of animal fodder such as hay were produced at Birka in the Viking Age. This is interpreted as only a small number of animals were permanently kept at Birka as well as an effect of the size of the island itself compared to the number of inhabitants during the Viking Age (Ericson et al. 1988; Wigh 2001:56; Risberg et al. 2002; Price et al. 2018). The zooarchaeological data from Wigh (2001) indicates a change occurred during the 9th century when Birka went from relying on sheep/goat and pig to cattle. This taxonomic change could reflect a change from a direct provisioning where the inhabitants were more reliant on their own subsistence provisioning, to an indirect provisioning system where inhabitants had to acquire their meat directly from merchants, pastoralists or farmers (Zeder 1988; Zeder 1998; Arnold et al. 2018). Consequently, this seems to fall in line with the information obtained from the isotopic data conducted for this thesis, perhaps with a shift even earlier based on the radiocarbon dates. The three taxonomic groups did not derive from the same location. The animals have isotopic values that points to multiple points of import, while some animals like pigs could have been kept locally.

Indirect provisioning reflects social stratification as also demonstrated in the study by Arnold et al. (2018), and the discussion of food provisions to the urban Bronze Age town of Tell-Safri/Gath. The subsistence change from sheep to cattle is strategically efficient since cattle provides more meat than sheep and pigs. The point made by Zeder (1988) in that cattle is an efficient animal for meat yield further elucidates to the fact that Birka must have had a well-developed network for import of meat. This type of organisation would not be necessary in a non-urban setting, as the production of goods for the economy would not be the main goal. Further, the osteological investigation of the 2015/2016 Harbour excavation gave insight to the representation of cattle as the dominant taxonomic group followed by pig, respectively (Wadstål 2021). The dominance of cattle and the representation of the entire skeleton indicates a walking commodity, where the cattle would also have been utilised for dairy before slaughter. Dairy does not keep well and would therefore be more suited to local production (Wigh 2001:107-109; Gaastra et al. 2020). The isotope analyses conducted for this thesis have highlighted the fact that the three animal groups derived from different places to various extents, which would follow the logic of multiple points of import in an indirect provisioning system.

Social stratification has by some been argued to be a key component of urban development (Arnold et al. 2018:7,8; Gaastra et al. 2020). The import of animals sheds light on a place in which subsistence was a secondary product while the main focus in the town were production of commodities for the broader market (Sindbæk 2007b). This coincides with Callmer (1994) and Ambrosiani (2013) accounts of the early urban towns in Scandinavia and the Baltic trading network that developed to accommodate the flow of trade and commerce. They both describes Birka as a place with interdependence to the hinterland and beyond. Further, this coincides with the principles outlined by both CPT and CFT. CPT revolved around central places and their connection to the broader hinterland. Birka would have had a central economic function compared to the hinterland. The people living in these central places had a foot in both worlds, with the benefits of the urban life and the goods from the rural hinterland (Skre 2012).

The principle of *Agglomeration economics* can also be applied here, the benefit of this interdependence between central places and the hinterland is further elucidated by the population growth in the Mälaren valley during the Viking Age (King 1985 [2020]; Wigh 2001). According to Wigh (2001:136) the benefit of supplying Birka and other such central places is evident in the fact that during the period between the 7th century and the 10th century the farms and rural places saw a population growth of nearly fifty percent. The benefits of the networks that surrounded these central places were reaped both in the central place itself and the hinterlands.

Centrality and urban status of Viking Age towns have often been based on the amount of goods and trading material compared to other sites of contemporary nature (Sindbæk 2007a). However, as highlighted by Sindbæk (2007b), these goods represents something that was once readily available due to these networks. Some places would perhaps have more of one type of good, while others had another type of good and dispersed this between them, which again will cause the archaeological record to have a skewed distribution of these goods (Sindbæk 2007b). Following the principles in CFT, this type of interdependence on the demand for goods and the goods for demand creates a flow, ergo a network between central places.

The Viking Age was a well-connected world system, attested to by archaeological material of long-distance trade. However the links that connected this world were not merely between central places alone but between central places and the entire hinterland (Sindbæk: 2007b). These socioeconomic networks provided food from the hinterland and Birka provided goods from the networks dispersed through the hinterland. Birka provided both the flow of goods, but also the urban lifestyle where work for a collective system were offered. The studies conducted by both Price et al. (2018) and Linderholm et al. (2008) tracing the origin of the inhabitants at Birka, and consequently shedding light in the multi-ethnicity that made up the human population at Birka attests to this. The archaeological material and isotope analysis from Birka and the hinterland, indicates that there was a substantial two-way street of interdependence in a large socioeconomic network. This is further indicated by the results from the research conducted for this thesis, whereas the animal isotope values indicate different points of origin for the animals, who ended their lives in this central place, which connected the Viking Age world. Consequently, the utilisation of methods such as isotope analysis has elucidated how tracing animal mobility can further broaden our understanding of these networks as a whole by tracing the previously untraceable, the animal mobility ergo the animal economy.

Furthermore, in tracing components of socioeconomic networks, light can be shed on aspects of societies and urban development that perhaps has not been investigated enough. The parallel of this interdependence can be drawn from the Swahili coast of Africa, where the development of the Swahili stone towns can be attributed to accommodate the trade in the region (LaViolette and Fleisher 2005:334-342). Swahili stone towns had an economic relationship with the hinterland which were possible through mutual economic interdependence and extended kinship networks (Kusimba 1999). The success and centrality of central places lies in bridging the divide between the core and the periphery. The broader socioeconomic network was tightly dependent on the hinterland, and its people. Providing the urban way of life, as a stark contrast to rural hinterlands, yet they were both connected. These deep roots to the hinterland were developed long before any influence from for instance Islam, which has been attested to the urbanisation status for these Swahili places. Previous research prior to the 1990's saw the African development as unimportant and not a phenomenon on its own, but something which had to come from outside influence, yet these Swahili places had developed a central status long before e(LaViolette and Fleisher 2005).

The parallel to the central places in the Viking Age are both contemporary and similar in connections between core and periphery.

The research history of urban and central places (often being one and the same) has been limited in the fact that trait lists and certain artefact classifications have been the main foci. The maritime aspects of places have taken centre stage in investigations of networks and trade economies. The connection to the hinterland has long been presumed, but not tested (LaViolette and Fleisher 2005). The problem with such categorisations as argued by Skre (2012), is that no matter how you categorise, it will always be wrong to some degree, as it fails to account for complexity. Further, as the examples of the Swahili coast demonstrates, sites like these develop to follow the times, they change, develop and decline accordingly, which underlines the social components of centrality and urban development, in which a trait lists do not account for (LaViolette and Fleisher 2005; Gaastra et al. 2020:19-20).

It has been argued that theories, such as CPT are flawed in the fact that they operate on static principles of development, and assumes a linear development to state (Sindbæk 2007b:61). The ^{14}C dates and isotopic values from this thesis attests to the import of animals before the historically set date of the Viking Age. The development of the links that connected the prehistoric world ebbed and flowed and were susceptible to change and not a linear development. The import of animals from near and far attests to both small and long links in the socioeconomic network of the time. Consequently, the Viking Age and its central places can be interpreted in the light of small world system theory, with a few, but central, urban towns that developed during this time. Birka, Hedeby, Kaupang and Ribe as argued by Sindbæk (2007b). The results of the isotopic values have elucidated a vast reaching subsistence network moving the gaze away exclusively from the trading component of the socioeconomic networks, and checklist adherence and turning it beyond it. In tracing animal mobility and the indirect provisioning system, to Birka it seems to appear as diverse as the town itself. This would mean that at any given farm in the hinterland, someone would have known or been related to someone with direct ties to a central place, such as Birka (Sindbæk 2007b; Smith 2014). It would then not be out of place to assume that the other central places in this socioeconomic network perhaps had the same far reaching provisioning system, which connects the divide between the core and the periphery.

7.2 Conclusion and future research:

Utilising a multi-isotopic approach to elucidate the socioeconomic network of animal mobility has shown great promise in determining aspects of socioeconomic development of central places. This approach gave the possibility to make a distinction between different dietary niches for the taxonomic groups. The utilisation of $\delta^{34}S$ in addition to $\delta^{13}C$ and $\delta^{15}N$ and $^{87/86}Sr$ values gave a valuable indicator of variation in diet with $\delta^{34}S$ values further highlighting different origins between the taxonomic groups. If only $\delta^{15}N$ and $\delta^{13}C$ values were considered, the interpretation of the diet niches would have been limited to terrestrial or marine protein components in the diet, and the results would have been interpreted quite different. The results of the isotopic research highlighted animals which clearly had been feeding on fish from brackish waters, according to their enriched $\delta^{15}N$ values, while their $\delta^{34}S$ values gave no indication of sea spray effect. $^{87/86}Sr$ analysis suggests the possibility for import of animals from a long distance away, while some pigs might have been kept locally. $\delta^{34}S$ enrichment indicated that some animals came from closer sea spray affected areas, or geological regions with higher $\delta^{34}S$ values than the local European granite of Birka and the Mälaren region. These variances in the isotopic data highlights that the taxonomic groups derived from many different locations, before ending up at Birka. By doing so, this study demonstrates a way to bridge the divide between core and periphery and bringing the hinterland into the equation of central places.

For all the findings in this research, the need for a broader isotopic investigation is inevitable to further elaborate on the findings for this project. More $^{87/86}Sr$ analyses would be valuable to elaborate on the different geographical origins between the taxonomic groups. In addition, a broader $\delta^{34}S$ isoscape for the Mälaren region and Birka would be valuable for further understanding the diversity of ^{34}S in the environment. For future research it would be of interest to sample the bone material from the Black Earth excavation to possibly compare different animal economies. This multi-isotopic approach would also be of great utility to other contemporary Viking Age sites, like Hedeby and Kaupang to further elaborate on the animal economy of the Viking Age. It would be of great interest to possibly be able to trace the animal mobility to the trade economy of the heterogenous socially stratified trading network. Lastly, more radiocarbon dates would be of great interest in probably dating the Harbour material, to establish if these dates actually indicate earlier urban activities.

This research falls within some of the grand challenges in archaeology, in how places develop, sustain, and decline in prehistory (Kintigh et al. 2014; Fernández-Götz 2018:148-

149). Perhaps also, moving the focus away from urban criterion merely focused on the urban site in question, and rather focus on what urban sites do, within all aspects of their existence. This is just the tip of the iceberg in investigating the subsistence economy and the socioeconomic prospects of the central urban places of the Viking Age, and beyond.

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Appendices

FigShare links to appendices materials:

SUERC Radiocarbon Laboratory, Radiocarbon results:
https://doi.org/10.6084/m9.figshare.16903003.v2

SUERC isotope raw data file:
https://doi.org/10.6084/m9.figshare.16902994.v1

Standards utilised by the SUERC radiocarbon laboratory:
https://doi.org/10.6084/m9.figshare.16857901.v1

RStudio codes:
https://doi.org/10.6084/m9.figshare.17013134.v1