The shell mounds of the Farasan Islands
-
An isotopic study of seasonality and coastal exploitation

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Abstract

The focus of this thesis is to assess the value of the coastal landscape of the southern Red Sea after the aridification of the environment following the early Holocene wet period (11,000–6,000 cal BP). It presents data from the Farasan Islands shell midden complex, encompassing over 3,000 shellmounds accumulated between 6,500 and 4,500 cal BP, and indicating heavy reliance on marine molluscs as food.

In the context of the overall aridity, there are crucial questions surrounding such intensive shellfish exploitation: a) were shellfish the main food source on the islands? b) were they a reliable food source and could they have supported a permanent settlement? c) was the exploitation of shellfish linked to the environmental change?

Exploitation patterns of shellfish are reconstructed using seasonality data based on 2,100 stable isotope measurements ($\delta^{18}O$ and $\delta^{13}C$) of the marine gastropod *Conomurex fasciatus* (Born 1778). This enables an assessment of the seasonal consumption of this species, and hence whether it could have been exploited all year round, or whether movement to the mainland (with its more temperate mountains) was necessary. Additionally, environmental data based on the same proxy is used to reconstruct climatic conditions. Early and late periods (6,500–4,800 cal BP) are compared to analyse the degree of aridity and the possibility of a longer-lasting early Holocene wet phase.

Results indicate that year-round shellfish gathering took place, with more intensive exploitation occurring in the summer dry season, and that 6,500 years ago climate was already extremely dry. This suggests that the intensive coastal exploitation was not due to landscape aridification, it also indicates that seasonal migration to the mainland was not a necessity, as shellfish were available throughout the year.

These results significantly extend the current understanding of subsistence strategies in the southern Red Sea and the value of shellmounds worldwide.

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Author's declaration

All of the work presented in this thesis represents the original contribution of the author and none of the results contained have been published previously or submitted for any other degree, unless stated otherwise. Appendix 2 includes the following publication, which is currently under review.

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Additionally, Dr Eva Laurie, Emma Tong and Dr Matthew Meredith-Williams carried out the faunal analysis of the shell midden assemblages discussed in this thesis. Dr. Katerina Douka carried out the analysis of radiocarbon dates where not stated otherwise. Prof. Melanie Leng and Hilary Sloane advised with the analysis of stable isotope data.

Chapter One

Introduction

1.1 Aims and objectives

In this thesis I focus on the large-scale depositions of shellfish remains on the Farasan Island archipelago in Saudi Arabia. During the mid-Holocene (6,500–4,500 cal BP) the Farasan Islands were a place of intense coastal exploitation, which resulted in over 3,000 shell midden sites that remain a dominant feature of the modern coastline. This high concentration of middens provides an unprecedented chance to study marine subsistence and large-scale shellfish harvesting on a world-wide scale (Alsharekh and Bailey 2014).

Whether coastal landscapes can provide sustainable food sources is the subject of ongoing discussions (Bailey and Milner 2002, Biagi and Nisbet 2006, Cavulli and Scaruffi 2013, Erlandson 2001). In some cases coastal sites are interpreted as marginal and the gathering of shellfish possibly as a last resort. Conversely, other researchers interpret coastal sites as being solely founded on available rich marine resources and even as the only place to have a reliable food source.

A reliable food source was important during the mid-Holocene in Arabia because the climate drastically deteriorated with the change in the solar insolation and corresponding southward movement of the Intertropical Convergence Zone (ITCZ) between 8,000 and 6,000 cal BP (Fleitmann et al. 2003, Lézine et al. 2014). The resulting weakening of the summer monsoon and the lack of precipitation caused wide areas of Arabia to become arid and, as a consequence, people had to adapt to this arid landscape. In this context it is often assumed that the expansion of desert conditions and increased aridity forced human populations to be more mobile or to migrate to more temperate environments. The grounds for this assumption are the lack of sustainable food resources available in this altered, arid landscape (Smith 2005, Veth 2005).

Well researched sites in East Arabia show evidence of the seasonal migration of herder communities between the temperate mountains and the coasts (Uerpmann et al. 2000, 2012). In contrast, other sites indicate groups with solely marine diets (Zazzo et al. 2014). For the Red Sea coastline, and the adjacent escarpment, which has a more temperate climate, the subsistence strategies are largely unknown. Earlier research (Zarins et al. 1980, Tosi 1986, Khalidi 2005, Durrani 2005) showed the prevalence of shell midden sites along the coastline but was not able to comprehensively link the use of marine resources to any form of subsistence strategy or seasonal movements to the mountains. Because the Farasan Island shell mounds are unequalled in their preservation, size and concentration, due to the remoteness of the islands, they are a prime example for the analysis of coastal exploitation, studies of seasonality, the sustainability of large-scale mollusc consumption and the marginality of coastal sites.

In this study I aim to assess a) how fundamental coastal resources were for the occupation of the Islands, b) whether they were able to support a permanent settlement on the Islands, and c) whether the substantial accumulation of marine mollusc shells was related to climate change.

When linked to the broader archaeological context, this will help to explain the possible movement of groups, the connection with people living on the mainland, and whether there are climatic reasons behind the intensive exploitation of marine molluscs. Furthermore, it will provide a basis for assessing the role of marine exploitation in deeper time periods in context with the southern gateway out of Africa.

To achieve this, the study intends to achieve the following objectives:

1. Establish the marine gastropod *Conomurex fasciatus* (Born 1778) as a valid environmental and seasonal proxy using the geochemical composition ($\delta^{18}O$, $\delta^{13}C$) of its shell.
2. Develop a statistical method to assess the accuracy of the isotopic signature and make the interpretation of seasonality more objective.
3. Determine the seasonal variations during the accumulation of a shell mound (JW1727) by applying stable isotope analysis to archaeological *C. fasciatus* shells, the main component of the shell assemblage.
4. Compare Farasan shell midden deposits of different periods and use stable isotope analysis to evaluate environmental change through time.
5. Use the results of the stable isotope studies to make inferences about how shell middens were part of a marine exploitation system on Farasan in particular and how the middens fit into the regional context.

1.2 Outline of thesis

Chapter 2 outlines the archaeological research that has dealt with mid-Holocene sites around the southern Red Sea with a focus on the Arabian Neolithic and on the research that has been done on the Farasan Islands in the past decade. It also discusses the role of coastal sites during the dispersal out of Africa via the southern Red Sea and the possibility of submerged sites in that area for which the Farasan Islands could be used as an ecological and archaeological baseline.

This is followed by an overview of the role of coastal sites and shell middens in general and the issues that are connected with their interpretation (**Chapter 3**).

Processes that lead to shell mound construction are reviewed as well as the factors that control the preservation of these sites. Additionally, shell midden sites of similar scale as the sites on Farasan are presented and I demonstrate how different processes can lead to the formation of big sites. Furthermore, I review the questions and sampling strategies of earlier seasonality studies and discuss the possibility of applying the same rationale to the Farasan middens. I further develop a field sampling strategy that combines the taphonomy behind rapid shell accumulation with seasonality data to measure individual occupation episodes on shell mounds.

Following this, the theory and methods of using stable ^{18}O isotopes for seasonality studies are explained (**Chapter 4**). The chapter also reviews different sclerochronological sampling methods applied to other types of gastropods and develops a new sampling strategy that is fitted to the morphological characteristics of the marine gastropod *C. fasciatus*.

The gastropod and the local marine environment are introduced in more detail in the following part of the thesis (**Chapter 5**). This establishes that the carbonate gathered from modern *C. fasciatus* specimens is a valid proxy for palaeotemperature reconstruction by comparing measurements of local temperature loggers and the $\delta^{18}O$ from modern shells collected over a 1.5-year period from 2012 to 2013.

Chapter 6 develops a new analytical tool to verify the likelihood of the season of death to make the interpretation of seasonality more objective. Additionally, I discuss the problems and anatomical biases of the shell in order to develop a targeting strategy for future research on the shell species.

Chapter 7 applies the information gained from the study of modern *C.fasciatus* (Chapter 5) to archaeological samples from the JW1727 shell mound, which was excavated as part of the DISPERSE project and as part of this thesis. The chapter describes the stratigraphic context of the samples and presents the results from the stable isotope study. Additionally, the statistical component of the study delivers a more objective view of the seasonality data, which is also combined with the stratigraphic information.

The results of the archaeological study are discussed in the following (**Chapter 8**). They are combined with the taxonomic data from previous studies about the shell mounds to answer questions about accumulation rates, marine exploitation, meat availability, and the sustainability of coastal life on Farasan.

This is followed by a discussion of how large-scale marine exploitation fits into the picture of coastal landscapes and the marginality of this kind of landscape in comparison to the desert hinterland (**Chapter 9**). Additionally, the implications of cultural exchange, seasonal movements, long-term mobility and inter-regional connections are discussed. Also the climatic changes recorded in shells from early and later shell mound deposits are presented.

Chapter 10 concludes this study by summarising the significance of the Farasan Island shell mound cluster. It also describes the potential for future seasonality studies in this area and others as well as the necessity of developing objective methods for seasonality studies.

Chapter Two

Archaeological background

2.1 Introduction

Shell middens on the coast of Saudi Arabia and other Red Sea countries have only recently been studied thoroughly (Bailey et al. 2013). This is partly due to their inaccessibility to international scholars and partly because researchers within the country have typically focussed on other aspects of their cultural heritage. Especially in Saudi Arabia the concept of cultural heritage management is still in its infancy. For example, only recently public relations between the archaeologists and the government on the Farasan Islands achieved an agreement that shell middens can no longer be targeted as easy access building material, one of the main causes for site destruction.

In this thesis I will use the term 'Neolithic' as a chronological description without any preconceptions about technological or cultural characteristics, which would be implied when used in a European context. 'The Neolithic' is a theoretical construct made by predominantly European archaeologists and does not have global applicability. In many parts of the world the Neolithic is defined as a period of sedentism and domestication, and, in many cases, a material culture characterised by pottery. The Neolithic of Arabia does not always fit into these 'general' descriptions but is much more variable, and sites from this periodcan have very singular characteristics (Crassard and Drechsler 2013).

The following sections will summarise research on prehistoric sites along the Red Sea. It will start with previous research on the Arabian Peninsula in general (**Chapter**

2.2) and the research along the Red Sea coast of Arabia in particular (**Chapter 2.3**). In comparison to this, a short overview on East African shell middens is given (**Chapter 2.4**), which despite their location on the other side of the Red Sea are closely related to the coastal population of Arabia. In conjunction to this, the theory of human dispersal via the southern gateway out of Africa is described (**Chapter 2.5**) as well as the potential of Palaeolithic sites that are now submerged and not yet part of the studied regional archaeology. (**Chapter 2.6**) The chapter concludes with an overview of the Farasan Islands and the archaeological research that has been carried out in the past years (**Chapter 2.7**).

2.2 The Neolithic period in Arabia

The Arabian Neolithic is far from being as comprehensive as it is in Europe and the Levant (Edens and Wilkinson 1998, Harrower 2008, Martin et al. 2009, McCorriston 2013). It is assumed that the Neolithic population of Arabia was much more mobile than its Neolithic counterparts in the north. McCorriston et al. (2002, 2005, 2012, also Crassard et al. 2006) researched the domestication and early herding of cattle in the Wadi Sana (Yemen). They divide Neolithic people into hunters and herders, and "dedicated pastoralists". The main difference between these two groups is the focus in subsistence strategy, with the former using herding only as supplemental food source and the latter fully concentrating on it.

McCorriston et al. (2013) see the shift to 'dedicated pastoralism' in the Wadi Sana at around 7,000 BP. This shift was accompanied by a population increase and vegetation management through fire setting, which indicates, if not sedentism, at least a certain degree of territoriality as these humanly-modified areas can be seen as an investment or an anthropogenic resource, which might even be worth fighting for according to Alvard and Kuznar (2001).

Following this, evidence of extensive herding areas were found in form of circular tombs with buried cattle skulls dating to 6,300 cal BP, indicating an increased exploitation of the landscape. However, dedicated water management and complex agricultural strategies appear to be much younger and only date to the 6th and 5th millennia BP (McCorriston et al. 2012). The timings for the use of domesticated animals as additional food source to hunting and gathering have not yet been determined. Also, how this increase in pastoralism is connected to the extensive use of coastal resources along coasts of the Red Sea and the Arabian Sea remains to be seen. Work by Uerpmann et al. (2000) in eastern Arabia suggested a combination of herding and coastal exploitation, while others assumed a much heavier reliance on coastal resources (Berger et al. 2013, Biagi and Nisbet 2006, Zazzo et al. 2014). However, these subsistence strategies chiefly rely on the region and their applicability to the West of Arabia is not clear.

2.3 The Neolithic in the Tihamah coastal plain

The Red Sea coastal plain of Saudi Arabia and Yemen is called Tihamah (Fig. 2.1). It mainly consists of fluvial deposits from the Holocene and is crossed by wadis that only seasonally carry water. Knowledge of the occupation of the Tihamah during the Neolithic period is based on only a few sites, which can be divided into the Jizan group in the North and the Hodeidah group in the South (Durrani 2005).

The Jizan and Hodeidah site clusters contain characteristic flakes that are typical for the Arabian bifacial group (Zarins et al. 1980) dating to the early Holocene 9,000-5,000 cal BP (Sanlaville 1992). The majority of sites from this period consist of lithic scatters with little depth and a general lack of stratified material. Given the nature of these scatters, they are difficult to date. The spatial distribution of lithics in context with shell midden sites can give some indication of their age, as the distribution of coastal sites and their distance from the contemporary coastline is consistent with the proposed rise in sea level since the last ice age and the subsequent fall at around 6,000 cal BP (Lambeck et al. 2011). The latter ended between 4,500 and 4,000 cal BP, when the modern coastline was formed (Zarins and Al-Badr 1986). However, individual site location cannot be used as a dating tool with high accuracy, since the distance of the midden to the palaeo shoreline during formation is unknown and the process of sea level change is unlikely to have been regular.

The shell middens in the Jizan area contain lithics of the Arabian bifacial type and are located on a palaeo shoreline about 10 km inland (Zarins et al. 1980, 1981, Zarins and Zahrani 1985). They were radiocarbon-dated to between 7,000 to 5,000 cal BP (Grigson et al. 1989, Zarins and Al-Badr 1986). However, the dated material was shell carbonate from unstratified shells as the overall analysis of the middens consisted mostly of surveying the surface. In addition, it is unknown to what degree wind deflation has eroded the middens. Traces of lithic processing and possibly fire-cracked rock were found, as well as a number of debitage and lithic artefacts, among them awls, denticulates, truncations, wadi pebbles, hammerstones, net weights, and backed flakes. Lithic material consisted of quartzite, basalt, andesite, diabase, gabbro and obsidian. The latter was found in the form of microblades small flakes, and debitage. The middens themselves were made of gastropod shells: *Strombus tricornis, Terebralia palustris* and *Turbo* sp. (Zarins and Al-Badr 1986). Apart from this the only faunal material consisted of heavily eroded mammal bones and ostrich eggshell, indicating a subsistence strategy that was focused on coastal resources (Durrani 2005).

The Hodeidah shell middens lie in western Yemen. There are few radiocarbon dates from these shells. Dates from the site Gahabah range from 6,000 to 5,000 cal BP and dates from sites in the Wadi Surdud range from 6,000 to 3,000 cal BP (Boivin and Fuller 2009, Durrani 2005). Again, the sampled shells were from the surface and their taphonomic background is uncertain, which introduces the same methodological problems that were found at the Jizan cluster. Bifacial arrowheads indicate a Neolithic tradition for some of the shell middens.

Obsidian artefacts from this period have been analysed using X-ray fluorescence (XRF) spectroscopy and compared to known obsidian sources from Saudi-Arabian and Yemeni highlands as well a number of sites from Eritrea but no connection was found. Khalidi et al. (2010) argued for the Eritrean sites to be more attractive providers for stone tool material for coastal groups, where resources would not have to be transported through the highlands but through the flat coastal landscape and across the Bab - al Mandab sea strait. This theory implies some degree of mobility and connections to African groups. However it cannot yet be proven without finding the lithic source. Cowry and dentalia shells have been found in inland sites 400-500 km from the coast (Edens and Wilkinson 1998). Their origin is unknown but at least indirect contact between groups over long distances was not impossible for people living in the Tihamah (Boivin and Fuller 2009).

The overall preservation of the Tihamah middens and the loose connection to inland sites makes it difficult to ascertain other activities that might have taken place in the vicinity of the sites. However, some indicators might point to a more diversified diet and lifestyle than solely shellfish consumption. Net weights were found as well as several ground stones (Durrani 2005). Additionally, several sites of the Hodeidah group, namely Ash Shumah, Gahabah, and Surdud-1 have a faunal assemblage containing bones from cattle, wild donkey, ass or sheep/goat. Some finds and their radiocarbon dates are questioned because of their poor preservation (Edens and Wilkinson 1998, Fedele 2008). However, it can be concluded that the use of domesticated cattle and the hunting of terrestrial mammals was also part of the subsistence of coastal communities.

A comprehensive interpretation of these sites is problematic as the preservation and low visibility lead to only a small amount of them being identified and thus generate blurred and distorted views (Wilkinson 2010). There is possibly a vast number of sites that have not been found yet and could be used to explore the wider context for the existing sites in the Tihamah as well as others in Arabia and Africa.

2.4 East African sites

Shell middens that are similar to the Tihamah sites have been found in Eritrea on the opposite side of the Red Sea (Bar-Yosef Mayer and Beyin 2013, Beyin 2011, Meredith-Williams et. al 2014a,b). The site of Asfet is located near the Gulf of Zula on a basalt ridge and was radiocarbon dated to ca. 5,500 cal BP. The main component of the middens are shells of *Terebralia palustris*, a large gastropod that can be found in mangroves. The lithic assemblage contained 411 artefacts, including tools, cores and non-diagnostic debitage made of mostly obsidian and some quartz or basalt. Compared to inland sites in Africa, the coastal sites lack evidence for fishing. There was no bone preserved and no finds that would be indicative for fishing or elaborate pottery as were found in contemporaneous sites on the Eritrean mainland (Beyin 2011). The relationship between these two types of sites needs further research to clarify how much they were in contact. Additionally, the relationship between Asfet and the shoreline is unclear as it does not appear to have been located directly at the coast. It is now located at a 1 km distance and none of the sediments in the vicinity indicate a closer location in the past. This is either due to the deliberate placement at a distant location from the water or due to the erosion of beach sediments that would indicate a shift of the shoreline away from Asfet.

Two sites that were found farther inland on the Buri peninsula date to this period (Beyin 2011). Gelalo, which dates to around 8,000 cal BP, is a shallow midden, with a thickness of 25cm, located about 15 km inland and covering about 400 m^2. Similarly to Asfet, it is located at a basalt ridge, but lacks any basalt tools. The lithic assemblage is mostly made of obsidian and consists of 4883 artefacts including tabular/prismatic blade cores, shaped tools and microliths. Again, like Asfet, the most dominant mollusc species is *Terebralia palustris*. Misse East, which dates to around 7,500 BP, is located 4 km from the coast and contrary to the shell assemblage at Asfet and Gelalo it is dominated by *Atactodea striata*, an intertidal bivalve (Bar-Yosef Mayer and Beyin 2013). The lithic assemblage from Misse East consists solely of obsidian material. Again the assemblage indicated the production of blades and microliths.

The differences between the three sites in selection of molluscs and the selection of raw materials for lithic production cannot yet be explained. Misse East and Gelalo had basalt outcrops nearby but there is no evidence of their use, which is possibly due to the good availability of obsidian. They are both closer to a known outcrop on the southeastern shore of the Gulf of Zula (Beyin 2011) but XRF analysis showed that there are at least 3 sources for the obsidian material (Glascock et al. 2008). It is obvious that more sites need to be analysed to get a better picture of how people were using the landscape and if there are major changes through time that contributed to a shift in the acquisition of lithic material. More than 600 possibly contemporaneous shell middens have been mapped on the Eritrean coastline north of Massawa, as well as on the extensive Dahlak Archipelago, using satellite imagery (Meredith-Williams et al. 2014b). Here several clusters were found, with two of them located on the rather small Nora Island (13.5 x 17 km) and another one on an island just off the main island, Dahlak (9 x 10 km). Three more clusters were found on the main island itself as well as shell middens outside of clusters covering the whole area along the palaeo shoreline, similar to the Farasan shell middens. However, no data exists on the composition or age of the middens and their relation to known sites on both sides of the Red Sea is until now only assumed.

In general, the Eritrean landscape during the mid-Holocene is still an area in archaeology with many blank spots. Contrary to Arabian sites, excavated middens in Eritrea are not closely related to shorelines and show a more intensive use of lithic material. The relationship between raw material sources and between the three sites is still inconclusive. The same is true for the relationship between the sites east and west of the Red Sea. The next section will present this relationship and show how it is more than likely to have been an intense one.

2.5 African-Arabian connections

Although Arabia is a large subcontinent on its own, it cannot be seen alone. Especially the vicinity of the East African coast on the other side of the Red Sea sparked several theories. In this context, the importance of the Red Sea shell middens was shown in the ongoing investigations of plate tectonics, sea level change, human dispersal and palaeoeconomies in the southern Red Sea (Al-Ghamdi 2011, Bailey and Flemming 2008, Bailey and King 2011), as the islands were possibly an important bridgehead for early humans leaving Africa in prehistoric times. This alternative route seems more and more realistic and has become an alternative to the traditional way using the Nile Valley (Dennell and Petraglia 2012, Mellars et al. 2013, Oppenheimer 2012, Stringer 2000).

It is likely that the now submerged coastline on both sides of the Red Sea was very productive and had beneficial conditions for human occupation (Bailey et al. 2015, Faure et al. 2002). Palaeoenvironmental research has shown that the Arabian Peninsula was experiencing a wetter climate during some episodes in the Pleistocene (Bailey et al. 2015, Lioubimtseva 1995, Rohling et al. 2013, Grant et al. 2012, 2014). This made it more attractive to early humans and also more accessible, since the lower sea level during the Pleistocene caused the Red Sea to be much narrower and have a wider continental shelf than it has today (Bailey et al. 2007, Flemming et al. 2003, Lambeck et al. 2011). Genetic data (Lahr and Foley 1994, Reyes-Centeno et al. 2014) and records of palaeolithic archaeology provide evidence for the theory of a human dispersal out of Africa using a southern corridor across the Red Sea to and through the south of the Arabian Peninsula (Mellars et al. 2013, Rose 2004).

The Bab al-Mandab strait plays a key role here as the narrowest part of the Red Sea and the most likely location of a crossing. Khalidi (2009) sees it as a likely passage for obsidian transport to Arabia during the mid-Holocene, when the sea strait was significantly wider and islands less prominent. For this passage, a direct crossing is not necessary and a step-by-step crossing is possible as well. This would include movements from island to island, which does not make special navigational skills necessary as the islands are not more than a few kilometres apart (Bailey 2009). Altogether, archaeological and geological information indicates that connections and frequent cultural exchanges between Africa and Arabia have been more than likely.

2.6 Submerged sites

The possible dispersal through the southern Red Sea, have led scholars to believe that there is a plethora of archaeological sites in the underwater areas along Arabia waiting to be found (Bailey 2004, Bailey and King 2011, Bailey et al. 2007, Flemming et al. 2003). However, the existence of a high number of submerged coastal sites has been questioned before, mainly because of the prevailing idea in archaeology that coastal sites are marginal. The following section will discuss the provenance of coastal sites in general and it will report on some of the underwater research that has been carried out in the Red Sea to find submerged sites. Although this thesis does not focus directly on understanding submerged sites, it is important to consider that the Farasan Islands are part of this wider landscape.

Sea level studies have a great significance for exploring coastal landscapes in archaeology (Chappell and Shackleton 1986, Flemming et al. 2003, Lambeck and Chappell 2001, Van Andel 1989). A central point of the research is the amount of coastal sites that start to appear at around 6,000 BP. It has been argued that this high number of middens is linked to the immense rise in sea level that came to an end at around the same time after rising over 100 m since the last glacial maximum. After the last ice age the sea level rise caused the oceans to inundate food sources that were previously inland, pushing human population into the former hinterland, crowding them and making it more difficult to keep up a subsistence strategy solely focused on inland food. Consequently, it has been argued that the reason for the rapid rise of shell middens around 6,000 BP was the result of demographic pressure and the subsequent competition for natural resources, forcing people to gather every possible food source, even the ones at the coast (Yesner 1987).

While the above theory sees the loss in inundated inland resources, others see the loss in inundated coastal sites and argue that they have always been high in number (Bailey and Milner 2002). Very early Holocene sites show evidence of coastal exploitation before the assumed scarcity and crowded population of the Holocene (Porcasi 2011). Additionally, coastal sites from the Palaeolithic or early Holocene were more intensive and focused on gathering shellfish than the theory of a marginal Pleistocene coastal activity would have allowed (Jerardino and Marean 2010).

Porcasi (2011) compared shell mounds of the Californian coastline from the late Pleistocene to the late Holocene. The total quantity of consumed animal flesh was calculated and it was found that shellfish in comparison to vertebrates had the highest quantities (89%) during the early Holocene. This percentage decreased around 9,000 BP with a slight gradual increase of vertebrates but general decrease of the total quantity towards the late Holocene, suggesting the use of plant material to substantiate their diet. This overall decline in coastal exploitation is directly opposite to theories proclaiming the expansion of shell midden construction in the mid-Holocene. The number of shell deposits predating the establishment of the contemporary sea level and the decreasing ecological activity both point towards an intensive coastal exploitation at sites that are now submerged. It is only the long distance to the contemporary coast that protected some Californian middens from sea level rise (Jones 1991, Fig. 2.3). This is why in some areas it is beneficial to concentrate on middens from steep coastlines as there is less lateral movement of the shoreline with a change in sea level. Additionally, the middens might have been occupied for longer periods (Rick et al. 2006).

The existence of submerged shell midden sites is likely even when arguing that they are the result of population pressure and smaller landmasses. If the gradual rise in sea level and assumed the overcrowding of the inland areas caused an increase of coastal exploitation, this change in subsistence must have been a gradual development. Consequently, there must have been an initial group of people mainly using shell middens in exchange for terrestrial food sources. These middens would be in the early Holocene and now also under water and thus missing in the archaeological record (Bailey and Flemming 2008). This does not necessarily contradict the meaning of coastal sites as solely an alternative food source to inland sites but it shows that there is a definite lack of coastal sites and a bias against coastal exploitation.

Coastal sites in the Holocene are also affected by changes in landscape formations which occur as a result of sea-level changes. In times with lower sea levels, the inland water table was lower as well, causing more highland aquifers to be depleted and the availability of freshwater at the lower coastline to be increased (Faure et al. 2002)a key factor favouring water conditions for vegetation on the coastal plain, which becomes attractive to animals and humans.

Some coastal sites predating the cessation in sea level rise are still above water, because of an isostatic uplift of the continental crust that is equally fast or faster than the rising sea levels of the ocean (Lambeck 2004). Some areas that were covered and pushed down by thick glaciers during the last glacial maximum experienced an uplift after the ice melted and the continental crust began to flatten out the dent left by the ice. This is the reason why early Holocene sites that should have been inundated if located anywhere else, are still above the sea level and are protected from submersion or erosion. This is a common trend of Scandinavian coastal sites (Hartz et al. 2007, Noe-Nygaard et al. 2005) and also in other tectonically active areas in Scotland (Bartosiewicz et al. 2010, Hardy and Wickham-Jones 2009).

Other sites, such as the Palaeolithic cave Pinnacle Point, are located at an equal altitude as today's sea level (Jerardino and Marean 2010). For parts of the period of its occupation (~170-90 kBP) the sea level was similar to the one established only 6,000 years ago (Lambeck et al. 2002). Pinnacle Point shows evidence of shellfish exploitation. It is debatable whether the number of shellfish remains (MNI = 99; Marean et al. 2007, Marean 2014) is comparable to mid-Holocene ones with tens of millions of shells (Bailey 1978). However, Pinnacle Point can still be interpreted as an early stage of coastal exploitation and has to be interpreted with the difference in population size and mobility between the Holocene mounds and the Palaeolithic cave midden in mind. The possibility exists that the site is smaller because the people that deposited the shellfish inhabited the cave for a shorter period and were fewer in number. Since today's sea level has not been at this level since 125 kBP (Lambeck et al. 2002) there are presumably more remains of shell gathering in between these periods, which are either submerged and invisible, or they have been destroyed.

It has now become common to assume that shell middens which seem to be a result of climatic change and population pressure (Cohen 1977, Osborn 1977, Yesner 1987), are actually more likely to be the most recent stage of an ongoing exploitation technique that has been used by many coastal populations for a long time (Bailey and Craighead 2003). This coastal activity might be, albeit still invisible, archaeologically very rich (Bicho and Haws 2008, Finlayson 2008, Erlandson et al. 2008, Jerardino 2013, Woodman 2013).

Specifically around the Farasan Islands, preliminary research on submerged sites has taken place in 2006, 2008 and 2009 (Alsharekh and Bailey 2014). Several diving surveys took place around the shoreline in different depths down to 60 m below current sea level. Although no new archaeological sites were found, geomorphological processes became apparent. The main problem with most sites is, if they are not eroded, they are likely to be covered by thick layers of marine sediment, which is why it is necessary to identify locations with a high potential for archaeological material (Momber 2000, 2004).

It was possible to locate submerged shorelines, which were indicated by traces of marine erosion forming wave cut notches (Alsharekh and Bailey 2014, Bailey et al. 2007, 2014a, b). These notches take time to form and are thus likely to resemble times of relatively stable shoreline position when sea level was lower. They cover a longer period than other areas and therefore have a higher chance of containing traces of occupation. It is assumed that they were used as dwelling places because the overhangs were good for providing shelter. This behaviour can still be noticed when walking along the modern shore that has minor accumulations of shell piles, fireplaces, and general garbage. Some shell assemblages were found underwater but because of species composition and a lack of anthropogenic material were decided to be natural (Pers. comm. Eva Laurie). Nevertheless, the surveys and bathymetric data achieved by sidescan sonar showed a highly variable landscape with a complex topography suitable to sustain all kinds of animal and human life (Alsharekh and Bailey 2014, Bailey and King 2011).

2.7 Research on the Farasan Islands

2.7.1 Climate and Tectonics

The Farasan Islands have a subtropical desert climate. The only water they receive is from the surrounding sea, and some precipitation from December to April with a maximum in monthly rainfall of 22 mm in February. Evaporation is much higher than rainfall but the groundwater levels are high enough to sustain some vegetation. Plants are also supported by the condensation of water from the very humid air (PERSGA 2000).

The average annual temperature is 30°C. January, the coldest month, has a range from 22°C to 31°C and July, the warmest month, ranges from 30°C to 38°C. The mean sea surface temperature in August is 33°C on average with a minimum of 32.1°C and a maximum of 33.9°C. It reaches a minimum in March with an average of 27°C with 26.5°C and 28°C as minimum and maximum, respectively. The tidal range is 1 m to 1.5 m and the water levels drop another 0.5 m to 1 m in the summer. Water salinity is one of the highest in the world and can reach 38.8 psu (practical salinity unit, also parts per mil) in November. It reduces to 37.8 psu just at the end of the wet season in February/March and drops even lower from late April to early July to 36.9 psu. The salinity is partly influenced by the seasonal inflow from the Indian Ocean through the Bab al Mandab strait (Siddall et al. 2004, Trommer et al. 2010). This inflow is connected to a change in wind direction from the Southeast in October to April and from the Northwest in May to September. This causes times of almost no wind, when the direction changes between the two periods. This sudden change can also be the cause of heavy rainfalls. During times when the southerly winds prevail, high saline waters in the north of the Red Sea are carried by subsurface currents into the south causing colder, less saline water from the Indian Ocean to flow on top of it into the Red Sea. In the same way, the northern winds drag surface water out of the Red Sea causing a subsurface inflow from the Gulf of Aden (Siddall et al. 2004). This inflow also injects upwelled water and controls the vertical nutrient recycling and increase in primary productivity in the southern Red Sea (Bouilloux et al., 2013).

The Farasan archipelago is part of the Arabian continental shelf, where the water depth is between 0-100 m deep (punctuated by deep depressions caused by salt tectonics) before the shelf drops off into the underwater canyon in the middle of the Red Sea. This area is highly influenced by tectonic uplifting and salt-plumes that uplift the fossil reef limestone that mainly makes up the Farasan islands (Bantan and Abu-Zied 2013). The islands are composed of five northwest trending lines that have mostly no relief. Only Farasan Kabir has areas of intense rifting and uplifting. Palaeo shorelines between the Ras-al-Gan and Khur Maadi still show former cliffs that have been undercut by wave action (Williams 2011).

Due to faulting experienced by the reef limestone, there are many cracks in the bedrock increasing the amount of rain-water that infiltrates the ground and makes up the groundwater reservoirs on the island. The water is easily protected by the fast infiltration and the overlying sediments have a low capillary action. The number and location of wells is unknown because many are in old farming areas which are now disused, but the number of freshwater wells seems to be much smaller than the ones with brackish water. Rainfall only happens in short episodes and it is not enough to sustain permanent wadis. Earlier wadis are now filled with silt and often used as farmland. When they stopped carrying water is not known (PERSGA 2000).

2.7.2 Archaeological Research on the Farasan Islands

The following section will describe the research that was undertaken on the Farasan Island with a special emphasis on two sites of major interest (KM1054, JE0004, Fig. 2.2).

Research was initiated to search for suitable prehistoric sites to clarify the possible migration through the southern corridor. The location of the Farasan Islands on the eastern shore of the Red Sea, and possible connections to other islands farther into the sea, makes them a favourable destination for hominins crossing the water. Bathymetric maps and shoreline modelling indicate a significant drop in sea-level during the Pleistocene. This made the Farasan Islands part of the Arabian subcontinent and uncovered several islands in the Red Sea making it easier to cross and making the connection to the Farasan Islands more attractive (Bailey et al. 2007, Lambeck et al. 2011).

During the first surveys it was important to find evidence for Farasan being occupied during the times in question and to clarify their role as coastal sites in the regional economy of the Palaeolithic. While Palaeolithic finds were made, absolute dates from this period could not be collected. However, during the first few surveys 2811 shell middens ranging from the mid-Holocene to Islamic periods were found (Figure 2.7.2). The Farasan Islands have extraordinarily favourable conditions for shellfish exploitation; the waters are warm and rich in nutrients providing a good environment for marine fauna (PERSGA 2000). The island population increased following the closure of a military base, and became generally more accessible, increasing development and fostering tourism. Within a few years, this almost unknown region had transformed to a key area in archaeology with the highest concentration of shell mounds worldwide (Bailey et al. 2013).

2.7.3 Previous excavations

Excavations were carried out in 2004, 2006, 2008, 2009, 2012, 2013 and 2014 on more than 20 shell middens, as well as 71 test pits along major palaeo-shorelines on the three bigger islands of the archipelago, Farasan Kabir, Qumah and Saqid, and some underwater locations to clarify their formation. The test pits showed a mostly uniform species composition of shell middens on the same coastline and presumably from the same period of occupation. Local concentrations of some species and other features such as hearths and thick fish bone layers were apparent in most middens and suggest different activities, although in order to make further interpretations larger areas need to be excavated (Eva Laurie, pers. comms.).

More detailed excavations were carried out at the sites KM1057 and JE0004 (Fig. 2.3). They were the subject of analysis for ecological studies and the analysis of site taphonomy (Williams 2011). They show two different kinds of shellfish exploitation on Farasan. Mostly, this is reflected in the diversity of their species composition but also in their different sizes, as KM1057, before it was eroded, was monumental and possibly four times the size of JE0004. Despite this, they seem to have been accumulated within a similar time span of both 300-400 years (Table 2.1). Especially for KM1057 this indicates an extremely rapid accumulation of shells. Given the comparable nature of the site studied in this thesis, JW1727, the following section will give a brief description of the structure and general composition of these well-studied shell mounds.

Site	Lab no.	Layer	^{14}C-Age	Mar. Res. Corr.	BP Range 2σ	Material	Species
JE0004	Beta-255383	Top (485)	5,010±50	-100±50	5,595-5,301	Shell	*Chama pacifica*
	OxA-19587	Base (436)	4,709±31	-	5,581-5,510	Charcoal	Unknown
KM1057	Beta-255385	Top (202)	4,880±50	-100±50	5,515-5,110	Shell	*Chama pacifica*
	Beta-255384	Base (284)	4,850±50	-100±50	5,595-5,301	Shell	*Chama pacifica*

Table 2.1 Radiocarbon dates of JE0004 and KM1057, after Williams (2011, Tables 10,12). Note that Oxa-19587 does not have a correction for marine reservoir effect as it is derived from a charcoal sample.

2.7.3.1 Excavation of JE0004

In the northernmost part of the Janaba East shell cluster a small number of shell middens sit on top of an undercut cliff made of the typical uplifted coral reef that makes up the main bedrock of Farasan (Fig. 2.4). JE0004 is the biggest midden in this group (~1.5 m deep, 20 m diameter) (Fig. 2.5), with a distinct location on a subtle peninsula overlooking and visible from most of the bay area.. The site was dated to 5,588-5,077 cal BP, but was probably in use as a processing site for much shorter than this. The site's youngest radiocarbon date originated from a cut into the midden that contained a burial. However, this burial is not necessarily linked to the shellfish exploitation that formed this midden.

While the inland side of the midden is a slight slope, the side facing the coastline has been heavily eroded and partially fallen into the sea as the cliff collapsed. Heavy wave action is an on-going problem in this area and intense cliff erosion near the site has been witnessed in the past few years. How much this influences the interpretation of the site in its relation to the shoreline during its occupation is open for debate. However for the sake of this comparison, JE0004 will be interpreted as having been close to the shoreline, because similar sites that do not experience erosive conditions can also be found on modern or palaeo shorelines.

The site was excavated using a 1 m wide trench through the midden from the inland side towards the water (Fig. 2.6). Several columns of bulk samples were taken and processed on site as well as in the laboratories at the University of York.

The overall volume of the mound was estimated by measuring the area of the exposed layers and extrapolating this to a circular disk each. This was tested against what had been excavated in the trench. In addition, the excavated material was weighed to estimate of the general volume to weight ratio, which resulted in roughly 1000 kg/m^3. *C. fasciatus* shells dominate (24%), followed by *Chicoreus* sp. and *Pleuroploca* sp. (33% combined) (Fig. 2.7). The overall mound was calculated to be 275m^3 in size.

The analysis of species composition by weight from bulk samples revealed that a large part of the layers are predominantly made of *Conomurex fasciatus* shells with values above 50% for almost all layers (Fig. 2.8). The bulk samples originate from several columns, as one single column through the midden would have ignored the spatial variability of layers throughout the section. In this context it needs to be mentioned that some layers show *C. fasciatus* in varying proportions, and that parts of these layers in other areas of the midden completely lack *C. fasciatus*. This is especially evident in the northern part of the midden. This overall spatial variability is possibly the result of inconsistent positioning of hearths but also of people sitting around the hearth processing fish (Binford 1968). The exposed section in JE0004 then cut through multiple centres of more or less circular shapes.

Generally, the exposed section shows two separate phases of exploitation at JE0004 (Fig. 2.6). One, a younger phase, is a package of stratified layers of *Chicoreus ramosus* and *Chama pacifica* in thick but unconsolidated deposits that make up most of the inland side of the mound. This is due to the nature of large gastropods, such as *C. ramosus,* but also due to the lack of sediment that would secure the shells within a matrix. Occasional pockets of *Conomurex fasciatus* can be found in association with charcoal and ash, as well as occasional *Pleuroploca* sp., *Pinctada nigra* and *Spondylus marisrubi*. Possible postholes were found as cone shaped disturbances that cut through several layers. More disturbance was introduced by two burials, which have been radiocarbon dated and were found to be much younger than the mound deposits, while still being associated to roughly the same period indicated by a lithic scraper found in the grave.

The second, an older part of the mound, is closer to the sea and mostly covered by the more recent phase. It is composed of *Conomurex fasciatus* layers that are separated by layers of ash and charcoal likely to represent hearths. The hearth deposits were sometimes associated with pockets of fishbone that could also be found in association with other layers. Also some layers of *Chicoreus ramosus* and *Pleuroploca trapezium* and *S. marisrubi*, as well as *Pinctada nigra* occurred. Some possible postholes were found which could have also been the result of other digging activities. The whole mound covers a thin layer of terra rossa on top of coral bedrock. This is the only place where this kind of sediment was preserved as it is not commonly found on Farasan anymore.

Preliminary results from MNI (minimum number of individuals) and size analysis of *C. fasciatus* shells throughout the midden showed a mixed picture of its ecology (Fig. 2.9). The MNI (represented by number of apices and supported by number of apertures) fluctuated but decreased gradually with a higher number of preserved apices towards preserved apertures in every sample. The overall weight of *C. fasciatus* specimens fluctuated inconsistently in relation to the MNI. Especially in the higher layers, both values seem to diverge. The average aperture size, which was used for the reconstruction of the total length of *C. fasciatus* shells, showed little variation throughout the midden.

A decrease in MNI was used to argue for a deterioration of the marine habitat of *C. fasciatus* and an environmental change that favoured rocky substrates rather than protected areas with shallow sand and calm water (Williams 2011). This change could have been caused by sea level change, with changing turbidity and wave action that exposes the rock surfaces and erodes the sandy sediment. Also the development of the coral reef in front of the beach could have changed the conditions for molluscs living in between both.

In summary, JE0004 is a relatively prominent site in the north of Janaba East that was exploited over a period of 328 years. Within this period, a shift from predominantly small gastropods to large gastropods occurred, but no convincing reason for this to happen has yet been found. Analysis of species composition and average shell size of *C. fasciatus* was only speculative, which is mostly due to the small amount of samples analysed at the time combined with the spatial variation of shell layers in the mound. The position of the site, its relatively big size, and the burial that was added subsequently, do imply some degree of importance in the general archaeological context.

2.7.3.2 Excavation of KM1057

The shell mound KM1057 in Khur Maadi Bay was excavated during a rescue excavation in 2009. It was under threat from bulldozing in the immediate area (Fig. 2.10) and by the construction workers using the shell as building material. The degree of erosion was substantial with approximately 60-70% of the mound already missing (Fig. 2.11). Radiocarbon dates from the base and the top of the mound give an estimated time period of accumulation of 382 years. KM1057 is part of a large shellmound group, where, in contrast to other areas, shell mounds do not simply follow the palaeo shoreline but also deviate from it and are arranged in clusters of 5 to 10 mounds in the immediate hinterland of the shoreline.

There has been some degree of tectonic uplift and subsequent draining of the bay area. The overall spatial distribution of sites around this former bay suggests that it had once been connected to Janaba Bay, splitting up Farasan Kabir into two separate islands (Fig. 2.2). The similarity in geomorphological change and how the sea level change might have impacted the shell sizes and overall coastal ecology makes it interesting to compare to the ecology of JW1727.

The excavated area was a section on the side of the mound that had previously been exposed by construction workers (Fig. 2.12). It revealed the clear stratigraphic sequence of the mound and the main species composition (Fig 2.13). Similar to JE0004, the mound is sat on a thin layer of terra rossa sediment on top of coral bedrock. This is covered by mostly *Conomurex fasciatus* layers that build up homogeneously without clear borders except where they are mixed with ash or charcoal deposits or are interrupted by mixed layers of *Chama pacifica* and *S. marisrubi*.

Based on the size of the layers and their composition, the overall species composition of the site was estimated (Fig. 2.14). Not surprisingly, *Conomurex fasciatus* was the dominant species (81%). The overall size of the mound was calculated to be around 880 m^3. This number includes the estimated quantity of bulldozed shell. But regardless of this introduced error, KM1057 is clearly a site that is multiple times the size of most other shell mounds.

Bulk samples were taken in 10 cm spits from the top of the mound to the bottom. The general lack of matrix in almost all layers except the hearths made it impossible to sample in multiple areas of the section or to expand it, because there was nothing to secure the individual shells and they easily fell out of the section. This was interpreted as an effect of rapid accumulation, which would prevent sand to blow into the mound and between shells.

The dominance of *C. fasciatus* is confirmed by analysis of the bulk samples. Apart from one of the top layers (sample 280) it is always present in great numbers. Even the lower layers of *Chama pacifica* and *S. marisrubi* show substantial amounts of *Conomurex fasciatus (*Fig. 2.15).

The preliminary analysis of MNIs and aperture length of *C. fasciatus* shows a more consistent picture in comparison to JE0004 (Fig. 2.16). The MNIs (again, represented by number of apices and supported by number of apertures) were consistent with the number of apices being higher than the number of apertures, barring one sample (70 cm) with high amounts of *Chama pacifica* and one sample (160 cm), where the *Conomurex fasciatus* weight was also exceptionally small (~0.9 kg) but its percentage in species composition was extremely high (99.7%) and there was virtually no sediment. The reason for this anomaly is unknown. The overall weight of *C. fasciatus* is consistent but steadily increases above the sample at 160 cm with a major peak just below the hearth area. The MNI of apices follows this trend, while the MNI of apertures remains the same. In comparison with JE0004, the average size of apertures is 22.9 mm while at JE0004 it is 18.9 mm. In general, it is apparent that this site is very different from JE0004 in terms of shell sizes and abundance. This is likely to be a reflection of the rich environment that is Khur Maadi Bay. The area between the contemporary shoreline and the shoreline contemporaneous to KM1057 must have been a shallow water environment with a lot of opportunities for subtidal and intertidal gastropods.

To sum up, KM1057 is a major site with a clear focus on intensive *C. fasciatus* processing. It is not clear, whether the size is also a result of deliberate selection of large specimens while gathering or only due to the local marine environment being shallow and probably more fertile than the more exposed area in front of JE0004.

Its location within a cluster of sites that do not only follow the palaeo shoreline but also other patterns, suggests that it might be close to habitation sites or other central places that life was focused on. The amounts of shellfish that were processed here (numerous times the amounts of what was available at JE0004) clearly indicate the importance of this area.

2.7.3.3 Excavations in 2013

During the 2013 excavations, 18 shell middens were excavated in different parts of Farasan Kabir. Research focused on areas around Janaba Bay (Fig. 2.17). Here a major palaeo shoreline and hundreds of shell middens were found and could be traced almost around the whole bay area. Middens on the palaeo shoreline, as well as in front and behind the shoreline, were targeted with the aim to excavate sites in different locations, which may reveal different dates or different functions, perhaps associated with different sea levels.

The excavations were separated into three major areas: Janaba West, in the North of Ras al-Ghan beach and in the South of Ras al-Ghan beach, and Janaba East at al-Ghadeer beach. All areas had large shell mounds that were accompanied by smaller shell middens and scatters. The shell composition for the larger mounds was very similar to the 2008 and 2009 excavations and mostly yielded layers of ash and *C. fasciatus* combined with smaller concentrations of other shell species. Among the other shells were *Pleuroploca, Pinctada, Chicoreus, Chama, Anadara*, and *Barbatia* species but often combined with *C. fasciatus*. The scatters showed a higher variability and were often composed of mainly one of the species above, especially big gastropods, and *C. fasciatus* to some degree.

Major mounds were often clast-supported and suggested a rapid construction, while scatters showed a high percentage of sedimentation, which is partly due to deflation and the general shallow layers made of large shells that are easily filled with aeolian sediments. Most shell mounds were constructed on beach ridges, which are natural deposits of small gastropods and crushed shells. In some cases, layers with a higher amount of sandy matrix were found that had small roots in them and almost the characteristics of soil. Some shell mounds had layers with very fine roots all through the section.

Although radiocarbon dates suggest that shellfish exploitation occurred over a 2,000-year period, single sites show different lengths of exploitation. Independent of size or spatial relation to other sites, the accumulation rates of some middens are very high (Williams 2011). This is reflected in layers with good preservation of shells in some mounds (KM1057, JW1807, JW1727, JE0087). The shells lacked signs of being crushed or having been exposed for longer periods. The opposite of long exposure can be assumed; these well-preserved shells were covered and thus sheltered immediately by new shell deposits.

During the excavation, only a small number of artefacts were found. Pottery was present on the surface of several scatters and in the upper layers, but is likely to date younger than the actual shell scatters and have been introduced to the upper layers through bioturbation. Two pieces of stratified pottery were found in the JW1727 shell mound in the North of Ras al-Ghan. The artefacts are broken potsherds with some encrustation and no real context apart from a mixed layer of *C. fasciatus* and *Barbatia* species. Shell midden JW5694 contained larger sherds of pottery in the same layers as mammal bones and a high amount of ashy sand with some charcoal. Its location below the bigger midden JW1727 located on the prominent palaeo shoreline suggests that it dates to a younger age as the sea level in this area dropped in the past due to local uplift caused by salt-tectonics.

2.7.4 Summary of archaeological research on the Farasan Islands

Shell middens on Farasan are so numerous they are almost a landscape feature. In comparison to other sites of the southern Red Sea they contain much less artefacts and cover only a time span of 2,500 years in total. However, they are a prime example for intensive shellfish exploitation with shell mounds of several metres in height and rapid accumulation periods with some accumulating vast amounts of shells in only a few centuries (KM1057). Also they may reflect the changes of the marine environment by tracking the availability of certain species that are characteristic for specific underwater habitats (JE0004).

Overall, they are evidence of the richness of marine landscapes in general and the southern Red Sea as focus point of African-Arabian exchange in particular. The middens are distinct shell deposits in pristine condition with only few sites showing signs of deflation or erosion. However, the growing industry and population of the island pose a threat to the preservation of these shell mounds.

2.8 Chapter summary

This chapter has shown that the southern Red Sea is an area with a lot of potential for interdisciplinary research, involving in archaeology, biology, geology, and palaeo-climatic reconstruction. How this relates to the rest of the Neolithic of the southern Red Sea and the corresponding inland areas can only be shown by the excavation of those sites. However, the sites mentioned above are extremely helpful in getting a glimpse of this period. The arid environment has led to some sites being pristinely preserved but also caused the destruction of others. The coastal environment especially shows rapid changes due to the tectonic activity of the Red Sea Rift but it is equally a landscape of intensive human activity and exchange. This interconnection of tectonics, submerged archaeology and coastal exploitation is unparalleled in the world. By studying these, we have the opportunity to explore the nature of these interactions and the impact on human occupation.

The surveys and research of previous decades are only preliminary but have shown the potential of archaeological sites during the mid-Holocene. The excavations at the Farasan islands are a valuable addition to the general archaeology of Arabia and the information about coastal subsistence that can be found within the sites can easily be applied to shell mounds sites around the world. More closely, the evidence of similar structures on the other side of the Red Sea shows how the Farasan islands are not simply an anomaly of the Tihama region, but a result of the richness of the Red Sea environment, the coastal dynamic of the tectonic landscape, and the efficiency of the coastal exploitation patterns that led to the construction of the shell mounds.

Chapter Three

Shell midden archaeology and research complexities

3.1 Introduction

One of the chief concerns of this thesis is the use of seasonality studies in archaeology. To discuss this, it is necessary to provide a brief background on shell middens in general and to explain the information that can be gained from them. This chapter provides an introduction to shell midden archaeology and the research problems that are involved. Various theories involving coastal exploitation will be explained and assessed.

Shell midden research is a major part of coastal archaeology, which often triggers intensive studies of coastal sites. Shellfish themselves are an important food source for all coastal communities, which is why their remains can be found all over the world. The term 'shell midden' is used to describe an anthropogenic accumulation of shells. Other names like 'Sambaqui' (in Tupi language, *tamba*: shellfish, and *ki*: piling-up) (Prous 1991) or 'Kjøkkenmøddinger' (Danish for kitchen midden), are used as well. The word Kjøkkenmøddinger describes a more diverse range of activities than simply shellfish processing since most middens also contain other traces of human life apart from shell, such as fish bones, burials, hearths, and even signs of structures. The presence of these other activities are also the main reasons why shell middens in general are defined as being of anthropological origin. In contrast, natural shell accumulations like shell beds have a different and less sorted species composition, varying sizes of shells or traces of animal accumulation (Green 1988). Smaller amounts of shell or shell deposits are sometimes called shell middens and, although they might have a dense sedimentary matrix and shells may not be the key component of the sites, they still give an insight into coastal exploitation.

The following section will begin with a general overview of shell middens and explore the different assumptions about the importance of shellfish in comparison to other food sources (Bailey and Milner 2002, Erlandson 1994, Sauer 1962, Yesner 1987) (**Chapter 3.2**). This is followed by an overview of the complications that are inherent to the preservation of archaeological deposits and the different preservation issues surrounding shell middens in particular (Luby and Gruber 1999, Bird and Bliege Bird 1997, Meehan 1977) (**Chapter 3.3**). After this, two case studies will be used to examine the different processes that lead to shell midden construction on a large scale (Gaspar et al. 2008, Schwadron 2013) (**Chapter 3.4**). The chapter concludes with a discussion of different perspectives on shell accumulation (Claassen 2013, Stein et al. 2003) (**Chapter 3.5**) and the application of seasonality studies to analyse accumulation processes (Finstad et al. 2013, Kennet and Voorhies 1996, Mannino et al. 2003) (**Chapter 3.6**).

3.2 The role of aquatic resources

Shell midden research explores and interprets the use and development of shell middens. However whether they are necessarily the focus of every coastal group is heavily debated. The following section will describe different interpretations of how prehistoric groups exploited aquatic resources and it will discuss the extent to which scholars think people relied on marine and riverine food sources.

Most scholars agree there is an intense relationship between hominins and water as a necessary resource to live (Newman 1970, Wheeler 1991). Inland water bodies are often areas of a high diversity of life in general. Where water meets land, the number of different species exceeds most other areas and supports fishing hunter-gatherers as well as non-fishing ones. Hence the importance of freshwater bodies in the human past is established. However, the importance of saltwater or brackish water bodies that make up the surroundings of coastal sites is more questionable In contrast to freshwater, saltwater is not required by the human body on a daily basis and therefore not inherently attractive to hominins.

But as many coastal sites show, the landscapes of estuaries, the meeting of freshwater and saltwater, is a very favourable environment (Bouillon et al. 2011, Bicho and Haws 2008, Eerkens et al. 2013). Similar to inland water bodies, coastal settings attract all kinds of life, including both animals and plants. These resources offer a variety of subsistence strategies to humans, whether it is the simple gathering of immobile shellfish at the shore or the more dedicated, complex forms of fishing using nets or pools (Bailey et al. 2007, Perlman 1980).

Despite this, the significance of coastal resources has been questioned in the past and many archaeological sites seem to back up contrasting interpretations (Bailey 2004, Bailey and Milner 2002, Binford 1968, Claassen 1998, Clark 1936, Erlandson 1988, 1994, Jones 1991, Osborn 1977, Parmalee and Klippel 1974, Perlman 1980, Price 1995, Quilter and Stocker 1983, Sauer 1962, Waselkov 1987, Washburn and Lancaster 1968, Wilson 1981, Yesner 1980, 1987). Put in a very simple way, Erlandson (1994) described opposing interpretations of coastal exploitation as either “Gates of Hell” or “Gardens of Eden”. However he emphasises that these view points are only the very extremes along a scale and that most interpretations are in fact far from these extremes. The interpretation as “Gates of Hell” picks up several arguments about how living in coastal conditions is much less preferable than living inland, especially in comparison with the hunting of big mammals (e.g. elk, deer), which are bigger and easier to process. Coastal sites are being interpreted in this argument as being marginal and the gathering of shellfish or other small marine animals possibly a last resort (Bailey 1975). The "Garden of Eden" concept interprets traces of human occupation along coastlines as being *solely founded* on the rich resources in the water and even as the only place to have a reliable food source (Mellars et al. 2013, Sauer 1962). Their main arguments against coastal sites being only marginal are the high population density and high complexity of the sites (Erlandson 2001). This is however still problematic, since population density is often difficult to ascertain (Osborn 1977) and complexity is a term often used without context especially among hunter-gatherers (Arnold 1996).

Bailey and Milner (2002) re-evaluated the stereotypical perception of coastal hunter gatherers and farmers in northwest-Europe and found many biases towards coastal communities in contemporary interpretations. They argue that coastal hunter-gatherer societies are being marginalised in order to fit into large scale trends. This has led to a simplification of the archaeological record, which implies a smooth transition from gathering to farming. A sedentary group of coastal hunter-gatherers does not fit into this broad picture (Schwadron 2013). Finally, they found that there is no evidence that marine resources were deliberately ignored by people in the past or that people who did exploit them were living a less successful life than their inland neighbours.

In the context of the Arabian Peninsula the aridity of the environment had a major impact on subsistence (Cremaschi et al. 2015). Earlier (Chapter 2) I described how various food resources were employed during the Arabian Neolithic and that in the Tihamah most archaeological sites were found in context of shell middens, implying that they relied mainly on coastal resources. This would fit well with the arguments for the use of shellfish as a last resort, because most terrestrial life would be less abundant as it would be too dependent on the sparse vegetation of the arid landscape. In contrast, however, there is evidence of movement and of herding in the Yemeni mountains close by (Crassard et al. 2006, Khalidi et al. 2013), which would mean that there are other, more preferable subsistence strategies available.

A similar situation was found in Oman and the United Arab Emirates (UAE), where some groups practiced herding while still moving to the coast (Uerpmann M et al. 2000) but other groups had a clear coastal subsistence (Zazzo et al. 2014). This opens up a question for both regions, the Tihamah and East Arabia; how marginal were shellfish as a resource, and to what extent where they a last resource? If the temperate environment of the mountains was close by, the practice of herding already known, and movements of other groups already happening, why do people decide to carry out the big-scale exploitation of an unfavoured resource?

The earlier research on the Farasan Islands has already indicated the general success of marine exploitation. Chapter 9 will discuss the results of this study fit into the theoretical landscape of exploitation patterns and general subsistence of people accumulating shell mounds.

3.3 Visibility and invisibility of shell middens

The preservation of shell middens and shells as part of the archaeological record will be the subject of this section. As described above, shell middens and coastal sites can often be difficult to interpret. A good understanding of the environment and connections to other archaeological features has a big impact on the quality of this interpretation. Additionally, it can be difficult to find them and to evaluate their extent. To analyse shell accumulations, it is important to account for all factors influencing preservation in the shell midden. Shell middens are often especially well preserved and often more likely to be found than simple constructions, hearths, or other traces of human occupation. Shells of any size or age accumulate fast, are very resistant to degradation and mounds of them can successfully shelter what is inside. This sheltering effect often increases when shell middens are located in cave sites or rock shelters (Claassen 1998, Jacobs et al. 2006, Stein 1992); a bias that needs to be considered.

Coastal sites are often seen as having better preconditions for site preservation. Many records of faunal material or animal remains derive from water bodies, due to the extraordinary potential for preservation of biological material in waterlogged sediments. In particular, water slows down decomposition by preventing oxidation. This is a positive bias towards sites around water bodies and it is hard to assess or to account for in statistics. However, not all coastal sites are waterlogged. Many erosive effects are also connected to water, found at coastal sites or rivers that experience wave action and strong currents. They have a very destructive effect on the habitats, not just of humans but also of other animals and plants, resulting in a very dynamic landscape that makes long-term occupation uncertain for people living in it.

Shell middens are more likely to survive these environmental impacts in coastal areas than other archaeological sites. Given their size and structure, the inside of a shell midden is often protected from environmental processes which can have a large impact on archaeological material outside the shelter of shell deposits. Hearths, structures, artefacts, and burials can become invisible. From a modern point of view, a site without traces of occupation and a site with destroyed traces of occupation can look exactly the same.

In this context it is important to emphasise the fact that on many sites the main living area is not directly on the shell mound or even within sight of it. It is an ecological assumption that it is unlikely for foragers to carry the shell further away from its source than necessary, which is often just outside the water. Thus it is also argued that shell middens resemble the palaeo coastline (Williams 2011). It is not always known what happened to the actual flesh within the shell, after it has been extracted near the shore possibly in some form of bulk processing to get rid of the extra weight and make the transport easier. The meat of the shells could have been taken away to any other dwelling for trade or as gifts, or even used as food while on the move. If evidence of occupation or other food consumption can be found on the midden it is likely that the shellfish was also eaten there. Layers of fishbones within shell middens are often associated with more local dwellings, since the fish were more likely to be eaten where the bones are located (Enghoff 1994, Sealy 2006). However, simple hearths can only indicate the processing activity to either make the molluscs easier to eat or just to get the animals out of their shells.

On the other hand, some argue that the animals are transported within their shells. Reasons for this are longer food durability and the need of people to find shelter or freshwater resources, or simply because of social habits (Bird and Bliege Bird 1997, Bird et al. 2002, Mannino et al. 2011, Meehan 1977, Waselkov 1987). Palaeolithic inland sites, which were at least 10 km inland, show evidence of coastal exploitation by the provenance of whole shellfish (Porcasi 2011). Accordingly, these shells become more prominent in the archaeological deposits, with the decreasing distance of the coastline due to sea level change (Bailey and Craighead 2003). These are only the cases where the transport of shellfish can be proven. The amount of shellfish that is carried off often remains invisible.

On a bigger scale, it is hard to clarify if the number of visible shell middens found represents the complete or near complete activities of human occupation, or if they represent complete shell midden deposits. In other words, it is possible that certain deposits remain invisible, due to shallow scatters that accumulated during short-term occupations or scatters whose accumulation rates were slower than the rate of decomposition and erosion, or if the shells were instantly cleaned up by the same people and transported somewhere else to put them to use or make room for new shells.

All these possibilities have to be considered when interpreting the remaining, visible shell middens and analysing their accumulation. Even a large shell mound with a high accumulation rate is subjected to the above-mentioned challenges and additional data has to be collected to account for them. On first appearance large shell mounds seem to be well preserved but single layers can still be missing due to shell relocation, short periods of erosion, manual truncation or other post-depositional effects. This is an issue that needs to be addressed and dealt with rather than just ignored or surmounted (Bailey and Galanidou 2009, Holdaway and Wandsnider 2008).

3.4 Building on a large scale

After describing the problems of the preservation and interpretation of shell middens, a brief report will be given on two well analysed shell mound complexes, the Sambaquis in Brazil (Gaspar et al. 2009) and the “Ten Thousand Islands” archipelago (Schwadron 2013), that are equal in dimension of shell exploitation with the Farasan Island sites. The examples will be used as examples for shell accumulation and to describe the driving forces behind large scale shell accumulations

The South American Sambaquis are a well known feature of the coastline as well as river banks further inland (Eggers et al 2008, Gaspar et al. 2008). These are large groups of shell middens of gigantic dimensions, often tens of metres in height, that can be found along the South American coastline. In a spatial analysis of the sites Gaspar (1998) defines three different domains (habitation, death, and the accumulation of midden material) that are associated with the Sambaquis in the areas of Rio de Janeiro, Sao Joao and Santa Catarina. The finds associated with each of the domains were found within the same shell mound and Gaspar emphasises the deep connection that the domains share within the life of the occupants. She argues that the mounds are the central living space of their occupants, which is indicated by traces of food processing and consumption like hearths and fish remains. Additionally, remains of wooden posts, clay floors and postholes as well as baskets and tools have been found (Gaspar 1998). A large quantity of incomplete or even broken artefacts implies that not only shellfish remains were easily disposed here. Additionally, 18.7% of the excavated Sambaquis contain human bones. They are thus interpreted as being not only a central living space, but also the most popular location for the disposal of the dead. This habit can be found in several Sambaquis throughout several periods and regions. Some mounds even show a specialisation in the deposition of bodies. The site Jabuticabeira II is believed to contain more than 43 burials. In particular, the deposits in the basal layers indicate a strong focus on funerary practices (Gaspar 1998). Additionally, features like postholes are often located with burial features and might have been part of a ritual practice. Many stratigraphic layers that were deposited to cover the burial sites are also the layers that contribute the most to the shell mounds' size, consisting of faunal remains in a sand matrix up to 60 cm thick. Some scholars even argue that shellfish is only a secondary part of the diet despite the size of the shell mound (Eggers et al. 2008, Klökler 2001). This theory alters the meaning of the mound because it suggests deliberate construction of a burial site.

With the high percentage of Sambaquis that contain burials and the associated features in the middens, it is reasonable to accredit the enormous size of some of them not only to the industrious exploitation of aquatic resources but also to a cultural practice that involves deliberate accumulation of shell midden deposits as part of a burial.

Further examples of shell middens of large dimensions have been found on the Ten Thousand Island archipelago, Florida (Schwadron 2013). Varying types of middens were found dating between 2,300 cal BP and 660 cal BP. Excavations at one of the larger sites, Dismal Key, were carried out and several occupation periods were uncovered (Schwadron 2010). In one earlier period, a large ring shaped midden of shells were accumulated and at a later period a system of several mounds over a wide area in a large arc was created. The shell ring is about 275 m wide and the nearby shell midden 'district' that is located to the west covers about six hectares. Both areas have been occupied at different times with a period of about 300 years between them. At the central shell ring, layers of clean oysters with no trace of matrix confirmed a rapid accumulation of shells. Remains of a structure were uncovered that were connected to several artefacts suggesting a high status individual. The extensive midden 'district' contained four major mounds of 5-8 m height and eight smaller mounds of 3-4 m height. Together they form a system of multiple exploitation locations containing ramps, portals and canals. This shows the deliberate use of shells as a construction material and evidence of intentional construction in general. But it also shows a gradual increase in intensity of shell exploitation, communal centralism, and a more elaborate hierarchical organisation throughout time (Schwadron 2010). Schwadron argues that with a change in spatial patterns, notably increasing size and special features made by reshaping the midden, there was also a change in social complexity. This change is coupled with more elaborate fishing techniques that were able to fully exploit the high coastal biological activity and produce shell mounds of this size (Widmer 1988).

These two described shell mound complexes are interpreted to have large shell accumulations because of burial techniques (in the case of the Sambaquis) and because of highly developed shellfish exploitation (in the case of Dismal Key). However, both examples also showed traces of living spaces, making it equally important that large-scale exploitation and burials were not the only factors shaping the mounds, but also shorter activities of individuals left smaller traces. The totality of activities that led to the construction of shell middens is poorly understood, as many processes can contribute to their growth. Often, middens are analysed as one unit and a general explanation for their formation is sought. How activities resulting in large and small scale shell deposition can be differentiated will be discussed in the following section.

3.5 Deciphering midden accumulation

Many factors may result in shell mound accumulation. This can make interpreting shell middens challenging, but understanding the *rates* of accumulation may help to decipher this. It is easy to forget that people using or accumulating shell middens did not see what archaeologists see today, but saw a smaller version of it, an “unfinished” version from a modern point of view. For the inhabitants, a shell deposition could have been “finished” when a grave was covered but in its whole a shell mound will never achieve a completed state and the people involved might have never had one in mind. Also, there are different intentions for shell exploitation and it would be implausible to simply classify a shell midden according to one single intentional background. Because people live in a dynamic world they can change their subsistence strategies and habits. Several factors, like group size, environmental conditions, or cultural characteristics (Bird and O’Connell 2006, Bird et al. 2002, Fischer 2007) can be found within a midden that can influence it simultaneously, thus making it hard to interpret despite the obvious burials and dedicated exploitation techniques.

Stein et al. (2003) try to break up these constraints by defining the accumulation rates of layers within shell middens on an absolute scale using radiocarbon dates. For this approach to be successful, several dating samples have to be acquired from the same layer rather than just from the top and the base of a midden. By comparing the results, different scenarios can be found, which mainly indicate a rapid accumulation rate, a gradual one, or a disturbed context (Stein et al. 2003, Fig. 2). The results are timeframes of the events or processes that led to the forming of one single layer and as a result the shell midden as a whole.

Using the accumulation rate of the midden, it is possible to argue that the midden was occupied or built up continuously rather than in the form of an event. This can be done with very large shell deposits and when the deposits are not very deep. If the layers are not very deep, a continuous accumulation would indicate that the rate of accumulation would not have been very fast. It also may suggest that the exploitation of marine molluscs was not a significant part of the subsistence strategy even though shellfish were constantly available. In contrast, if the layers suggest only an occasional build-up, the shells can have only been available or were only exploited in certain periods. It can also be argued that these shallow, interrupted layers were not the cause of a variable availability of the food source but of a mobile society that only visited for a short period of time.

To conclude, the processes that lead to the construction of a shell midden are various. Not simply eating, but eating with particular incentives, will have an influence on accumulation. In addition, depositional processes linked to social or ritual behaviour – activities, which can be difficult to see archaeologically – may be at work. Additionally, for any large shell accumulation, one thing can be assumed: to be able to perform any processes with a high accumulation rate, one must have access to a readily available food source and inexhaustible supply at least for the duration of the accumulation events. This, combined with the lack of other food sources, people's unawareness of other food sources or simply a preference for marine food, can lead to large mounds of shell of several metres depth, depending on the length of occupation and sustainability of the marine population.

Altogether, it is key to be able to reflect the whole range of possible subsistence to make statistically valid assumptions of people's habits on a daily basis as well as over long periods of time.

3.6. Seasonality

3.6.1 Introduction

Interpreting seasonal patterns in food exploitation has been part of many prehistoric studies in the past (Andreasson et al. 1999, Carter 1998, Fitzhugh 1995, Legge and Rowley-Conwy 1988, Mannino et al. 2003, Monks 1981, Quitmyer et al. 1997). It is an important concept for understanding resource availability, butchery practices, and subsistence patterns. It can also reveal information about social complexity and belief systems linked to seasonal cycles (Monks 1981).

The main principle of seasonality is that people perform different activities at different times of the year, and that life is repeatedly controlled by seasons of plenty and seasons of scarcity (Harrison 1988). For hunter-gatherer groups this also implies a necessary movement and a change in subsistence. Lack of settlements and efficient storage facilities is often the reason why hunter-gatherers are thought to have moved to where they can find fresh food (Smith 2003).

Food availability is of importance to understand as most proxies for seasons of occupation are the food remains found on site. It is unlikely that all consumed food has left traces in the archaeological record, thus, often only well-preserved food-related proxies like shell or bones can be used. This bias has to be considered. Equally, food remains can only be used to argue for certain seasons but not against others (Milner 2005, Andersen 2013). However, although it is not possible to capture the whole variety of consumed foodstuffs, seasonality data can still be used to get information about how lives were structured and what factors influenced characteristic customs and habits connected to food.

The following section describes aspects of seasonality and various ways of interpreting them. From this I draw assumptions about how seasonal signals from the

Farasan middens can be interpreted and introduce a sampling method with a detailed stratigraphic component that would theoretically allow to analyse the accumulation of single episodes of deposition.

3.6.2 The application of seasonality

This section reassesses the use of common theories regarding seasonality data and explores how applicable these concepts are in the Red Sea context. It will focus on three major theories regarding seasonality: 1) environmental changes, 2) site significance, 3) group movements.

Environmental changes are thought to have influenced seasonal food availability in the past. In Northern Europe people struggled with a lack of plant resources in winter (Bokelmann 1971). In Pacific America seasonal and other regular upwelling events caused times of extreme marine food availability and triggered its frequent exploitation (Andrus et al. 2005, Jew et al. 2013a, b). In contrast, Southern Arabia is on a latitude that does not experience seasonal change of the environment as profoundly as other areas of the world. Additionally, the desert climate is likely to have had a negative effect on the availability of terrestrial food throughout the whole year (Arz et al. 2003, Lézine et al. 2014). How much of the terrestrial food sources survived in this arid environment and how terrestrial food availability changes throughout the year is unknown. The same is true for marine resources, which could be linked to the seasonal nutrient inflow from the Indian Ocean (Bouilloux et al. 2013).

The categorization of shell middens into large, permanent or ephemeral sites has been achieved using patterns of seasonality. (Culleton et al. 2009, see also Jones et al.

2008). If sites are identified as permanent base camps, they may have been a significant place for prehistoric communities - the place where the prehistoric life mainly took place (Kowalewski 2008), although this has recently been disputed (Eerkens et al. 2013).

The shell mounds of the Farasan Islands do not show the same variety of sizes or clear traces of constant habitation. Some shell mounds are aligned in clusters but the majority are still mainly following the coastlines. Whether there was a clear division into more ephemeral or more permanent places of marine exploitation is not apparent. Rather, a majority of sites appear to be part of the general subsistence strategy and others are outliers.

Seasonal accumulations of shell mounds may imply seasonal population movements. A seasonal movement from one place to another has been proposed for Californian shell mounds (Eerkens et al. 2013). Seasonality data has been gathered at two sites (CA-SFR-171 and CA-SMA-6). These sites complement each other in seasonal signals (derived from shell seasonality data), which suggests there has been movement from one site to another in different parts of the year.

The existence of shell mounds on many parts of the Farasan Islands is proof of multiple places of shell exploitation. However, there are difficulties in applying the above method. In contrast to the Californian middens that are multiple kilometres apart, the Farasan shell mounds are only a few dozens of metres apart, albeit covering a coastline of many kilometres. The sites are not far enough apart to argue that there has been significant movement. Studying two sites that are far apart and finding different seasons of exploitation would not be as revealing when there are a hundred sites in between. Hence, when reconstructing the mobility of people, the Farasan shell mounds cannot be seen as separated sites or as single locations of shellfish exploitation. They need to be interpreted as an area of shell depositions similar to extensive sites in Denmark (Andersen 2000), South Africa (Jerardino and Marean 2010), or Brazil (Wagner et al. 2011). Given that habitation sites are poorly preserved on Farasan (Bailey et al. 2013), it is difficult to ascertain from where on the islands people actually moved to exploit shells on the coast. This leaves us with a much more basic understanding of movement. To untangle this, it would help to compare sites with larger distance in between, such as sites from the Tihamah or islands between the Farasan Islands and the mainland. Also a comparison with contemporaneous sites that might be found in the more temperate mountains in the future could help to assess seasonal movements.

The plethora of sites across the whole archipelago, in combination with the lack of obvious habitation structures, forces us to rethink the analysis of seasonal indicators at this site. Clearly, permanent sites or smaller, “hunting camp”-style sites have not been found. Seasonal changes in the environment, which may have resulted in distinct changes in the landscape, affecting the human population, are unknown. Spatial analysis is made difficult because of the practically homogeneous distribution of the sites along the coastline and seasons of harvest can only be interpreted as being valid for the whole island. However, this does not mean that the seasonality data needs to originate from hundreds of shell mounds distributed over the Farasan Islands. A single mound can still be interpreted as a single entity and can provide valuable information. The different aspects involved in connecting seasonality data to different parts of a single mound, and the linking up seasonality data with stratigraphic sequences will be discussed in the next section.

3.6.3 Finding single episodes of accumulation

In the previous chapters I outlined the rapid accumulation of shell material that has been found at other sites (Chapter 2.7). It is likely that because of rapid accumulation many of the Farasan shell mounds provide a high resolution record of depositions that can be accounted for in the sampling strategy. This depositional record can be used to ask new questions about shellfish exploitation and depositional processes happening on site. Given that the accumulation is rapid enough and stratigraphic information is appropriately detailed, it should be possible to follow the methods of Stein et al. (2003) and use seasonality data as a measure for accumulation rate. The following section describes the problems with addressing these questions with the use of three case studies. This is followed by a sampling strategy for the Farasan shell mounds that would take some of the problems of the case studies into account and enable the analysis of high-resolution records of deposition.

The nature of archaeological sites is that they can be analysed on multiple scales and from different perspectives. Archaeological sites are palimpsests of many traces of activities overlapping with each other, blurring earlier traces or even erasing them. All of this happens at different times and on different time scales. To analyse all activities and processes of a site, questions need to be asked on multiple scales according to the subject of the question. Bailey (2007) describes this phenomenon as Time Perspectivism. He writes, "*that different timescales bring into focus different sorts of processes, requiring different concepts and different sorts of explanatory variables*' (Bailey 1987, p. 7).

There is no other way to see the whole picture, and every activity or variable that influenced the archaeological record, other than using multiple scales or perspectives. By looking only on one single scale, we either miss the single activity or we miss the overall trend. The questions that can be proposed are inherently linked to the site and the dataset itself. Of most importance for this are the excavation or sampling methods that are applied when the site is excavated. For example, if there is no apparent stratigraphy, then a site cannot be excavated in stratigraphic layers but only in spits. It follows that the data from the excavated material can answer no questions that require knowledge of individual stratigraphic layers.

Contrary to this, sites excavated with a detailed stratigraphy can more easily answer questions regarding the whole site. This means, provided there are no gaps in the record, that a high stratigraphic resolution can answer more questions than a low stratigraphic resolution of the same subject.

Radiocarbon data and the enormous amount of shell remains (e.g. KM1057) indicate a very rapid accumulation of shell and an industrious system of food procurement. Seasonality data combined with detailed stratigraphic documentation can provide information on how many shells were deposited at a time or within a season during a single episode of occupation. This study proposes to analyse the amount of shells that accumulated during a single episode of exploitation or multiple shell depositions within a short time period that can be picked up by seasonal signals. However, in order to analyse and interpret a single process that built up a specific layer, the samples with the seasonality data need to be excavated on an appropriate scale.

In an ideal world, each single deposition would lead to a distinct layer that could then be analysed for its seasonal signal. A cluster of these subsequent depositions would represent a seasonal occupation period of several weeks, months or the whole year. The gradual change of the seasonal signal from layer to layer throughout the stratigraphy would be recorded completely. However, the case studies below will show that this is not the norm. Many sites have a low or infrequent accumulation rate; others have indistinct layers that can only be excavated using arbitrary spits. Few seasonality studies can divide their shell assemblage into distinct layers to show the origin of the data and thus cannot interpret the seasonal variation from layer to layer, forcing them to interpret the seasonality data in bulk instead (Burchell 2013; Culleton et al. 2009). The following examples will be used to explain some of the requirements for the excavation of shell midden sites, which enable the seasonality of single accumulation episodes to be addressed. These requirements are related to the resolution of the sampling method in the field. Mainly this is expressed in the size and distance between the sample units throughout the column. In this context, I also discuss the use of size and age distributions in combination with seasonality data.

Kennet and Voorhies (1996) recorded the stratigraphic context of the shells they used for seasonality data from the Tlacuachero shell mound in Mexico. They were able to analyse specific units distributed over a complete column of the shell mound. They extracted 20 specimens of *Polymesoda radiata* from 7 spits of 10 cm each. However, the spits were 40-100 cm apart and covered a period of about 2,500 years. Evidently, the mound has not accumulated as rapidly as has been found in Farasan sites (Chapter 2.7) but even if it had the sampling resolution would be far too small. Taking 20 specimens from a 10 cm area of a column provides a good insight of the sampled area but it leaves huge gaps in between. The data cannot be representative for the whole layer, partially because of its size and partially because it does not include the full extent of the layer itself. When searching for single episodes, the boundaries of the layers need to be considered and the sampling units must not leave any gaps.

A more thorough approach to column sampling has been carried out by Finstad et al. (2013) on a shell midden on Brooks Island in the San Francisco Bay Area. 30 shell specimens were taken out of each of 14 of the 16 existing spits in order to analyse the seasonal variability of the occupation periods. Each spit covered 6 inches (15.24 cm) of the section without any gaps in between. The seasonal variation of the site showed the exploitation of *Mytilus trossulus* predominantly occurred from summer to late fall and occasionally in late spring. A more thorough division of sample areas into layers rather than arbitrary spits was not possible because the shells had been excavated in the 1960s and were part of a museum collection. This lack of archaeological context makes it hard to interpret the seasonality data and find single episodes of deposition. Additionally, unclear stratigraphic units make it more likely that the shell deposits have been disturbed and the stratigraphic units are not in order of time of their deposition. More critical in this context is the spit size of 6 inches as the smallest measurable scale. To find a single season of accumulation with this scale, it would need to be a very localised accumulation and a very rapid. Every deposition with a slower accumulation, or one that is spread out over a wide area, cannot be sampled on this scale and would become mixed with underlying and overlying depositions. Following this, the size of the sample unit of which shells are being extracted from needs to be as small as possible.

Mannino et al. (2003, see also Mannino and Thomas 2001) applied a thorough approach to the analysis of shellfish exploitation at the Culverwell midden, UK, which resulted in the identification of single episodes of seasonal accumulation. By using shells from spits within each layer and comparing their individual age distributions, they were able to find a decrease of shellfish age within subsequent spits of one layer. They deemed it likely that this impact was caused by the continuous exploitation of shellfish. In combination with this, seasonality data was able to show that most of those shells were caught in seasons with similar isotopic values and the values showed a gradual increase indicating a slow but constant change in season. The isotopic values from within one layer were then interpreted as being connected to the decline in shell age that was tracked within the spits of the layer, which made it possible to interpret the intense exploitation as single episodes over several months.

3.6.4 Sampling method for measuring the accumulation of single episodes

The immense shellfish availability on the Farasan Islands makes it less likely that a similar situation to the unsustainable exploitation strategy at the Culverwell midden can be found here (Bailey et al. 2013). The main component of the middens is the marine gastropod *C. fasciatus* (Chapter 2), which was repeatedly accumulated in vast amounts along the coastline and is likely to be abundant enough that it could not be obliterated within a few seasons (Williams 2011). Mannino and Thomas (2001) were able to postulate a constant exploitation period because of the indication of overexploitation throughout the spits, and interpret the seasonal signals from the overall layer as sequential rather than disconnected. At the Farasan Islands, it should be possible to postulate a similarly sequential episode of exploitation based on high resolution stratigraphic information (i.e. smaller spits) that is added to the seasonal signal.

Provided that sampling strategies are employed at a resolution that is similar to the amounts of deposition (which are mostly unknown) it should be able to find single episodes of deposition and measure their rate of accumulation. To maximise the sampling resolution of each layer, this study uses a sampling resolution of 5 cm. This 5 cm scale is based on two conditions, (1) the nature of *C. fasciatus* shells is that they cannot be excavated on a much smaller scale than 5 cm because each individual shell is several centimetres large, and (2) the assumption that there is a minimum amount of shells that the collector finds sufficient enough to carry out the processing procedure. Since the meat that can be gained from a single *C. fasciatus* shell is about 2-3 g based on field observations, I argue that there were several hundreds to thousands of individual shells that accumulated within a period of occupation. This would have easily taken the shape of a layer of more than 5 cm. Excavations showed that visibly identifiable layers in the middens are more than 5 cm in size and often so big that each layer can be split into a top, centre and base sections of 5 cm each, realistically making it possible to capture the starting season and the end season of the layer. Multiple sites in close vicinity can also mean simultaneous processing of shells, which further strengthens the point that the amount of shells that were processed and deposited at a time was more than a single hearth could handle, facilitating the argument towards thousands of shells and rapidly formed layers.

In theory, when sampling shells in layers of 5 cm and finding only one seasonal signal, it is possible to argue that these 5 cm have accumulated at the same time and are not the result of multiple periods of deposition that are years apart and coincidentally show the same season of occupation. This result can be used to make assumptions of how much was exploited in a certain amount of time, how rich the local molluscan habitat was, and how much was eaten before the location was deemed to be not profitable anymore. Additionally, a multi-season result within a 5 cm layer can be interpreted as a low-activity period.

The results of the seasonality data in this study will not just be used as an indicator of how often people processed shellfish, and if there are seasonal differences in this processing, but also the theory will be tested that seasonal sublayers can be identified within the stratigraphy. These will then be able to help to understand how middens accumulated on a seasonal time scale, introducing another perspective of interpretation.

3.7 Summary

This chapter gave a brief background of shell midden archaeology and its various theories and biases. It showed the difficulties in approaching a type of site that is composed of waste material, which is mainly connected to only one type of subsistence. That the shellfish remains might be overrepresented in the assemblages is a big possibility and needs to be considered when interpreting shell midden sites and their significance. When shell midden sites show a major importance in the landscape and are the result of big scale exploitation, their role within the social context still needs explaining. In this context a shell midden can fulfil multiple roles throughout its construction from a minor scatter to a midden of monumental size in its final form that we see today.

I use the background of large shell mounds and how they accumulate to lead up to a new application for seasonality data. A comparison with other seasonality studies shows the importance of asking the right question to the assemblage. The special case of the Farasan shell mound cluster changes most questions and approaches of analysing seasonal movements or the importance of the midden in the seasonal round. This is why I explore a new scale of analysing shell accumulations by proposing a method where shells are identified in context with their stratigraphic information. The precondition of a rapidly accumulated shell mound, as has been shown on Farasan, is vital for this approach.

Chapter Four

Stable isotopes and Sclerochronology

4.1 Introduction

Stable isotope analysis measures the ratios of non-radiogenic isotopes, which vary according to external environmental or internal metabolic factors. This tool is valuable to many research areas in archaeological science.

The advantages of stable isotope analysis in archaeology are not new, and have been enlisted for the analysis of artefacts, human and animal remains and sediments from archaeological contexts. The main concept of stable isotope research on shells can be found in the beginning of sclerochronology studies, which is “the study of physical and chemical variations in the accretionary hard tissues of organisms, and the temporal context in which they formed.” (Jones et al. 2007).

I apply this concept to the shell remains from the Farasan islands for the reconstruction of seasonality data. More specifically, I apply it to the marine gastropod *Conomurex fasciatus* as it is found in most excavated layers and most surveyed shell middens (Bailey et al. 2013). No detailed research has been done previously on *C. fasciatus*. Demarchi et al. (2011) were the first to scientifically investigate the species in context with its potential for dating using Amino Acid Racemisation (AAR). However, for this no detailed information about the mobility of the mollusc, its feeding behaviour, reproduction, lifespan or shell accretion is necessary. Hence, no thorough enquiry of the mollusc needed to be carried out (Beatrice Demarchi, pers. comm.). Other research on the mollusc is currently on-going and involves analysis using Raman spectroscopy on the shell pigments. First results show that the shell is comprised of pure aragonite (Andre de Lima-Ponzoni, pers. comm.). A detailed description of the methodology and results of the Raman analysis can be found in Appendix 2.

In the following section, I build on this previous knowledge of *C. fasciatus*. I provide the necessary background for the application of stable isotope analysis to study seasonality and present studies on similar shell species, which produced results that might also be applicable to *C. fasciatus*.

The chapter will begin with an explanation of the principles of shell growth (**Chapter 4.2**) and how they have been researched in the past (**Chapter 4.3**). This is followed by a closer look at the application of stable isotopes in sclerochronology and the limitations of the different analytical methods that have been applied (**Chapter 4.4**). The chapter concludes with a discussion of different sampling methodologies (**Chapter 4.5**), in the context of the development of a sampling method for *C. fasciatus* (**Chapter 4.6**).

4.2 Principles of shell growth

Growth line formations in molluscs follow a simple process that mainly includes the formation of calcium carbonate and organic material during aerobic and anaerobic states of the metabolism. In the state of aerobic metabolism, molluscs deposit calcium carbonate in the form of aragonite or calcite in combination with organic material enclosed into the shell structure. This whole process produces the mollusc's most recent shell layer ($CaCO_3$) and acid (H^+) by the following chemical reaction:

$$Ca^{2+} + HCO_3^- \rightleftarrows CaCO_3 + H^+ \quad \text{(Eq. 4.1)}$$

The aerobic metabolism is associated with periods when the mollusc is exposed to well-oxygenated waters, such as high tide, and when the shell is open. In contrast, during an anaerobic state (e.g. times of shell closure) the amount of acidic components in the shell-building fluids rises and is gradually neutralised by the calcium carbonate of the shell, resulting in a dissolution of the calcium carbonate and a higher percentage of organic material in the layer deposits (Crenshaw 1980).

Many other factors can play a role in the different ratios of organic material to calcium carbonates. Extreme events like spring tides, storms, or extreme temperatures can have an effect on the mollusc's metabolism and can cause it to rapidly change into an anaerobic state. Equally important are changes that are linked to the physiology of the mollusc. Spawning events or other causes of stress can have a strong impact on the shell growth (Kennish 1980). In gastropod shells it has been shown that the availability of food has a significant influence as well (Schöne 2008).

The produced shell carbonate has different characteristics depending on the mineral components (aragonite and calcite) that are specific for each mollusc species (Leng and Lewis 2014). These minerals can both occur on their own, mixed together or separated into different parts of shells. This is important for two reasons. Firstly, to reconstruct palaeo temperatures from each mineral, a different equation needs to be used for each mineral (Grossman and Ku 1986; Kim and O'Neil 1997) and secondly, aragonite is thermodynamically unstable and can convert into calcite at high temperatures, which changes the isotopic signal (Sand et al. 2012).

4.3 A Historic Overview of Sclerochronology

Charles B. Davenport first described how growth lines in shells can resemble past climate conditions (Davenport 1938). In the following decades the main use of this concept was to answer questions about past climate in geological contexts (e.g. Berry and Barker 1968) but initial approaches to archaeological use and seasonality studies were also made (Rhoads and Pannella 1969). Monks (1981) summarises the results of seasonality studies that followed and their methodological restrictions. He also briefly touches upon early stable isotope research by Shackleton (1973) and described it as too sophisticated due to the amount of expertise and equipment that is needed to carry out such research (Monks 1981).

Shackleton performed an elaborate application of Urey's study by using fossil carbonates to reconstruct palaeotemperature (Urey 1947). Shackleton was the first to describe how to gather the potential archaeological data in growth lines of archaeological shellfish using geochemistry.

Aquatic molluscs grow shell increments when they are alive and submerged. These increments reflect the isotopic components of the surrounding water and in this way build up a record of water chemistry throughout their lifetime. For Shackleton, the important part of the water chemistry was the ratio of the oxygen isotopes ^{18}O and ^{16}O. This ratio is expressed in units per mil (‰) using the following equation

$$\delta^{18}O = ((R_{sample} - R_{standard})/R_{Standard})* 1000 \quad \text{(Eq. 4.2)}$$

where R is the ratio of ^{18}O over ^{16}O in the sample or the standard and $\delta^{18}O$ stands for this ratio within the sample. If $\delta^{18}O$ is negative, the sample is depleted relative to the standard, if it is positive it is enriched relative to the standard. Because molecules with heavier isotopes have a stronger bond (Gat 1996), ^{18}O is less inclined to evaporate than ^{16}O. Thus both isotopes react differently to temperature change and the ratio will change accordingly. Additionally, this difference between heavy and light water molecules leads to characteristic ratios for marine waters and freshwater because the latter mainly consists of evaporated water.

Ultimately, this ratio can be found in shells that recorded the isotopic composition during the mollusc's lifetime (Fig. 4.1), which can then be analysed to produce a local environmental record (Shackleton 1973). This can give an insight into temperature and salinity of surrounding waters, seasonal variations in these, and long-term changes related to climate change (Fig. 4.2).

For the $\delta^{18}O$ values from aragonitic shells (hereafter $\delta^{18}O_S$), the empirically derived temperature equation of Grossman and Ku (1986), adjusted for the $\delta^{18}O$ of water (hereafter $\delta^{18}O_W$) (Dettman et al. 1999), can be used to estimate the Sea Surface Temperature (SST) for the moment of shell growth.

$$SST\ (^{\circ}C) = 20.6 - 4.34\ (\delta^{18}O_S - (\delta^{18}O_W - 0.27)) \quad (Eq.4.3)$$

4.4 The application and limitations of stable isotopes in shell studies

After initial attempts to use stable isotopes on shells for palaeoecological studies (Killingley 1981, Shackleton 1973), many advantages (Deith 1986) but also restrictions have been found (Bailey et al. 1983, Monk 1981, Schöne 2008). The initial simplicity of this approach is now made more complicated by the understanding of several factors that influence the outcome of these studies significantly.

These factors are chiefly connected to metabolic processes occurring in the mollusc while it is alive, which control the manner and rate of shell growth. Ignorance of these processes will mean that the data will be difficult to interpret, as isotopic values can be over or under emphasised or simply missing from the record (Schöne et al. 2006). Goodwin et al. (2003) described the different patterns of shell growth throughout the year (Fig. 4.2). Their graphs mainly focus on two easily visible factors that affect shell growth. The first is the change in increment widths due to age and the second is the organism's shutdown during extreme temperatures when no increments are being created and temperatures are not being recorded (e.g. Fig. 4.2 B: hiatus from December to January). The illustrations are heavily simplified but show how much the interpretation of the isotopic record depends on information about the mollusc.

This is the reason for a series of publications on isotope studies on modern specimens showing that the object at hand is a viable tool to answer the archaeological research question (Barrera et al. 1994, Lartaud et al. 2009, Mannino et al. 2003, Jones and Quitmeyer 1996, Radermacher et al. 2009) and that understanding the modern specimen is still the agreed first step of the methodology. The reason for this is that each species has its own unique reaction to environmental, metabolic or ontogenetic changes, which can lead to a bias in isotopes ratios (Mannino et al. 2008).

For the $\delta^{18}O$ from shell carbonate to act as a proxy for palaeotemperature, the relation between the isotopic composition of the water that the shell lives in and the isotopic composition of the shell carbonate needs to be resolved. The change in the first has to cause a change in the second. Several calibration studies took place to successfully correlate the calcium carbonates derived from modern shells (Epstein et al. 1953; Grossman and Ku 1986; McCrea 1950), synthetic aragonite (Tarutani et al. 1969), gastropods (Rahimpour-Bonab et al. 1997) and coralline sponges (Böhm et al.

2000) with the isotopic composition of the surrounding water. These studies indicate that $\delta^{18}O$ derived from the water is indeed reflected in the $\delta^{18}O$ of the carbonate of these species.

In addition, the geographic location of the shells needs to be climatically stable enough and show a regular and predictable seasonal variability in temperature and salinity - the two main factors that influence $\delta^{18}O$. Areas that show no change and do not record significant variation are not as useful in picking up seasonal changes and, hence, drawing conclusions about the seasonal influences on the shell. Equally, areas that have no consistent changes that are dissimilar from year to year cannot be used as a reliable proxy. As $\delta^{18}O$ is controlled by two different factors, i.e. temperature and salinity, which are integrated in one value, it is necessary to exclude or control for one of the factors from the equation (Eq. 4.3) (Ferguson et al. 2011; Schweikhardt et al. 2011). This is either resolved by using additional isotopes or choosing a location where one of the variables shows little to no variation in temperature or salinity.

In conjunction to $\delta^{18}O$ the carbon isotope ratio ($^{13}C/^{12}C$ resulting in $\delta^{13}C$) is determined. $\delta^{13}C$ is often used as an indicator for marine or terrestrial diets (DeNiro and Epstein 1976, Chisholm et al. 1982, Lee-Thorp et al. 1989, Craig et al. 2013), with lower values in terrestrial sources and higher values in marine sources. In marine molluscs $\delta^{13}C$ can be helpful when measuring changing salinities, for example in estuarine environments (Gillikin et al. 2006). Freshwater in rivers generally has a lighter $\delta^{13}C$ because of the input of CO_2 from decomposing terrestrial plants. The freshwater outflow from rivers into the sea carries this lighter terrestrial carbon, which influences the carbon isotope composition of the estuarine and marine environment (McConnaughey and Gillikin 2008). This is subsequently recorded within the shell of marine molluscs because the shell is predominantly made of the

CO_2 and the dissolved inorganic carbon (DIC) in the water (Leng and Lewis 2014). Other influences, such as primary productivity, ontogenetic processes or food availability have also been shown to factor into the $\delta^{13}C$ values of marine shells.

4.5 Sampling Methodologies

Sampling strategies of molluscs mainly depend on the research question and the specific species. Because stable isotope analysis is expensive, researchers need to make a compromise between many measurements per shell and the number of analysed shells. This is connected to the sampling resolution on the shell (i.e. the amount of measurements per shell).

Not all sampling methods aim to answer questions about seasonality. Studies that use land snails as an environmental proxy use bulk analysis of stable isotopes, where the complete shell is crushed and pulverised. A subsample of the resulting powder is taken after it has been mixed thoroughly. This way the analysis will show an average isotopic composition over the lifetime of the shell (Colonese et al. 2013, Yanes et al. 2009). This methodology has a low resolution because it compares the different environmental conditions between the lifetimes of the shells, such as precipitation and vegetation. Many shells are part of one study to account for variation between specimens and to cover the whole range of possible average isotopic compositions.

Other environmental studies gain climatic records from within one single shell with a long life span. Bivalves like *Arctica islandica* are often used in these studies because of their longevity and broad geographic distribution. Many carbonate measurements are taken from different growth increments in a sequence within one shell and the resulting curve shows climate change in a much higher detail (Schöne et al. 2013).

However, the large number of samples per shell also means cutbacks on the amount of shells that can be analysed. This results in the exact opposite of the land snail analysis above where one sample per specimen is taken but the variation within the assemblage is much clearer.

For seasonality studies it is ideal to have many specimens available to answer questions about seasonal variability within the archaeological context, and also to have a clear record of the environmental change. This record is necessary in order to assess the isotopic composition of the last growth increments of the shell, that can then be related to an isotopic composition that is typical for a specific season within the annual range of $\delta^{18}O$.

To achieve this ideal, various approaches have been used. All of them are a compromise between the certainty of the season in the shell and the seasonal variability in the archaeological context, depending on the subsequent cost of the analysis. With a good understanding of the seasonal isotopic compositions and the general growth rate of the shell, a short sequence of measurements starting at the most recent growth increment and following the direction of growth, should pick up the general isotopic trend of the previous months and concluding in which season the mollusc died. While publications have made use of only two consecutive samples (Culleton et al. 2009) or even less (Kennet and Voorhies 1996) it is apparent that the chance of a valid result rises with the number of consecutive samples. The following example demonstrates the problematics of using a short sequence of samples.

The shell midden site CA-ALA-17 in the San Francisco Bay is a homogenous shell deposit of oyster (*Ostrea lurida*) and clam (*Macoma nasuta*) shells that covers an exploitation period from 4,000 to 1,500 cal BP (Culleton et al. 2009). The radiocarbon dates and the artefacts found on site put CA-ALA-17 into the Early and Middle Archaic

(Milliken et al. 2007), however a continuous occupation is unlikely. Seasonal movements have been proposed for semi-sedentary people inhabiting the Californian coastline during the Archaic. Thus, Culleton et al. (2009) aimed to analyse the seasonal character of the site. However, they based their seasonal interpretation on only two sequential shell edge values from *M. nasuta* shells (n=36) and apply a sample distance of 2 mm. The rationale is that there will be three kinds of $\delta^{18}O$ two-point sequences: an upwards slope, a downwards slope and a horizontal line, which can be assigned to the seasonal maximum or minimum. The results show that most two-point sequences had either an upwards or downwards trend in $\delta^{18}O$ values. The slopes were then used to interpret the site as being occupied in summer and winter, the seasons with warming and cooling trends in the local environment.

There are systematic errors with this approach. The method does not make it possible to distinguish between two-point sequences that follow the seasonal trend and two-point sequences that only show a slope because of standard error or an anomalous measurement which caused different values. Even more importantly, the method does not account for changes in growth rate. All samples are 2 mm apart, but how this translates into time is not necessarily regular, as growth patterns can be irregular from one individual to another and depending on the season. This can result in unequal time frames being covered and different times of the year being compared.

These factors introduce an error for the penultimate $\delta^{18}O$ value on the shell and a bias towards sequences with unequal $\delta^{18}O$ values because it is more likely that the two values are different rather than similar. This is why the seasonality of the overall site shows an emphasis in seasons of change (summer: n=13, winter: n=14) rather than stability (spring: n=7, fall: n=2). There is an inherent bias in the analysis that cannot be accounted for, which leads to invalid interpretations.

An increase in the number of measurements taken along each shell edge would help to increase the robustness of the interpretation because additional samples can give an estimate of growth rate as well as minima and maxima of the seasonal curve. Furthermore, they help to rule out when $\delta^{18}O$ values are anomalous.

Jew et al. (2013a,b) assessed the advantage of longer sequences at the early Holocene sites on the Channel Islands, California. At the site SMI-693 on San Miguel Island they found that 35% of their samples from California mussel (*Mytilus californianus*) needed to be assigned a different season when they used a sequences of 6 measurements instead of 2 measurements for sampling (Jew et al. 2013a). Identical results were made at CA-SRI-666 on Santa Rosa Island (Jew et al. 2013b).

This means that a minimum amount of samples needs to be found to be able to make clear assumptions about the season of death. Since shells growth rates are different, there is no general number for all taxa that scholars could agree on. The most economically feasible number of measurements has to be found for every species and every growth rate.

In addition to stable oxygen isotopes, the analysis of trace elements has been applied as a second temperature proxy. By combining $\delta^{18}O$ and the Mg/Ca ratio, Schweikhardt et al. (2011) made good use of estuarine conditions in the San Francisco Bay that are influenced by a change in salinity as well as temperature. Similar to $\delta^{18}O$, the Mg/Ca ratio depends on the temperature during calcification. The relative amount of Mg increases with temperature because the substitution of Mg for Ca in aragonite is an endothermic reaction (Rosenthal and Linsley 2006). So both ratios depend on water temperature but only the isotopic composition of oxygen isotopes is also controlled by salinity. This made it possible to plot clusters of seasonal values from modern shells on a $\delta^{18}O$ and Mg/Ca grid. The clusters are arranged in an almost circular shape. This means that only the composition of the last growth increment of archaeological shells needs to be analysed to determine the season of death. Since only two samples per shell (one for $\delta^{18}O$ and one for Mg/Ca) need to be analysed to plot the shell specimen onto the $\delta^{18}O$ and Mg/Ca grid in comparison to the seasonal clusters, it is a very cost efficient method that can make use of many specimens.

4.6 Sampling Conomurex shells

The chosen proxy for the analysis of seasonality on Farasan is the marine gastropod *Conomurex fasciatus* as it is the main component of most shell mounds and a key resource for coastal exploitation on the whole archipelago. No isotope research has been done previously on *C. fasciatus* shells before the start of this study. Previously *C. fasciatus* was named *Strombus fasciatus*, which is why here I compare it with studies on shells from the *Strombus* genus under the assumption that they share a similar shell anatomy.

A common characteristic of *Strombus* shells is the characteristic lip, which grows on the aperture when they reach adulthood. This distinction will be used more often and throughout the thesis I will refer to the juvenile and adult parts as equivalents to the main body (=juvenile) and the thick lip on the aperture of the shell (=adult) (Fig. 4.3).

The information gathered from the study of other species in the *Strombus* genus was extremely useful. Geary et al. (1992) started work on *Strombus gigas* shells from various locations and looked at how the carbon and oxygen isotopes are affected by inherent biological processes and also environmental changes like salinity, temperature, and seasonal upwelling. They especially looked at ontogenetic trends that were shown to deplete the shell in ^{13}C in correspondence with reproduction.

They sampled the shells along the most recent whorl with a 1 mm sample distance using a 0.5 mm drill head. Additionally samples were taken from the penultimate whorl to the protoconch with a 3-5 mm sample distance and also 1-2 samples from the lip part of the shells. The change in sampling resolution is based on the assumption that the younger parts of the shell grew quicker and thus experienced less isotopic change over the same distance. The 1-2 samples on the lip part of shells were used to compare juvenile and adult parts of the shells and check for ontogenetic trends.

The analyses showed that $\delta^{18}O$ values in *S. giga*s represent the general change in temperature and salinity, but the values differ from one location to another, making it imperative for studies on archaeological shells to compare modern shells living in the same habitat as the archaeological ones. They also showed a rapid growth of shells during juvenile stages with over 8 cm/year. More importantly, they showed that there is no obvious correlation between $\delta^{13}C$ and reproduction. The comparison of values from juvenile parts and adult values from the lip showed little ^{13}C-depletion and in some specimens even higher values in the lip. For $\delta^{13}C$ in *C. fasciatus* this could be helpful as it possibly also rules out some age related biases.

Radermacher et al. (2009) sampled several specimens of *S. gigas* shells from the Caribbean. The temperature variation of the local environment of 25ºC to 30.5ºC was not recorded completely as there are no isotopic values in the shell carbonate that correspond with temperatures below 26.5ºC. This may suggest a growth stop below this temperature and a hiatus in growth rate sequence. This is however different from another analysis carried out in Bermuda on specimens of the same species that did grow below 26.5ºC (Wefer and Killingley 1980). The reason for the different ranges is not clear.

One aspect of *S. gigas* shell growth are the distinct purple and brown lines that appear during times of reproduction and food scarcity causing a cessation in growth. The growth pattern in the shell's flared lip contains the isotopic record of the past half year within only 12 mm of sample area, while the pattern in more juvenile portions of the shell accumulates over 200 mm of shell growth for the same amount of time in the isotopic record (Fig. 4.4). This is even more rapid than what was recorded in previous *Strombus* shells. The difference in growth rates makes it necessary to sample on different scales using different sampling resolutions, depending on the rate of growth and age of the shell. Radermacher et al. applied a sample distance of 8–12 mm on the juvenile parts of the shell, and <1 mm on the lip part of the shell.

The fact that there might also be distinctly different growth patterns within the *C. fasciatus* shell makes it necessary to analyse the changes towards the lip parts of adult shells very closely.

4.7 Summary

This chapter showed that in theory sclerochronology and stable isotopes have a great potential to analyse seasonal and climatic changes in the environment. It also showed, that there are a lot of general and species-specific unknowns. This is true for the local environments of the analysed specimens and also for the anatomy and shell structure of the analysed species. The results of previous research provide the initial information for the method that is used in this study. They will help to efficiently analyse the shell structure of *C. fasciatus* and assess to what extent it records the seasonal change in stable isotope composition. Studies on shells of the *Strombus* genus showed that there is a vast differences in growth rates between juvenile and adult parts of the shell. Also it was shown that juvenile shells can grow extremely rapidly, to the degree that large distances between the sample measurements (3-5 or 8-12 mm) did not result in an insufficient sampling resolution. On the other hand they showed that even large gastropods like *S. gigas* with a shell height of over 23 cm need a high sampling resolution (<1 mm sample distance) in the adult parts of the shell. How this applies to the much smaller shells of modern *C. fasciatus* from the Farasan Islands will be analysed in the next chapter.

Chapter Five

Modern study

5.1 Introduction

This chapter is about the study of modern *Conomurex fasciatus* shells to provide a control on the interpretation of stable isotope values in the archaeological material. The outcomes of the field work on Farasan as well as all the different analyses of modern *C. fasciatus* that were carried out to build up a sampling method for the seasonality study are described. Six field seasons were carried out over a 1.5 year period: November 2012, January-March 2013, May-June 2013, September 2013, December 2013 and February-March 2014. In all field seasons it was possible to collect temperature and salinity data, collect water samples from different parts of the island, as well as survey and collect living specimens of *C. fasciatus.*The underlying theme of this chapter is the equation by Grossman and Ku (1986) adjusted by Dettman et al. (1999) to accurately reconstruct temperatures from shell carbonate (Eq. 4.3). In this equation the values for temperature (**Chapter 5.2**) and general composition of the water (**Chapter 5.3**) are used to estimate the $\delta^{18}O$ (hereafter $\delta^{18}O_{est.}$) that should be recorded in the shell at different times of the year. Following this, the $\delta^{18}O_{est.}$ values and the $\delta^{18}O$ values from the modern shell edges ($\delta^{18}O_S$) are being compared (**Chapter 5.4**), ideally they should be the same. Additionally, I discuss the probable $\delta^{13}C$ change throughout the year and its implications for shell growth and isotopic composition. The chapter concludes with a growth analysis of modern *C. fasciatus* based on the measurement of growth increments, explorative mapping of Mg/Ca ratios with a high resolution using laser ablation, and on the sequential $\delta^{18}O$ and $\delta^{13}C$ values, which enables the development of a sampling method with a sufficient resolution for seasonality studies (**Chapter 5.5**).

5.2 Temperature and salinity data

5.2.1 Data acquisition

General information about the temperature and salinity of the southern Red Sea is available and has generally been previously described (Chapter 2.7.1). Additionally, local measurements of temperature and salinity were taken over a 1.5 year period using two data loggers (Star Oddi DST CTD) (Fig. 5.1), in order to more thoroughly investigate the local environment of Farasan and to see if the archipelago follows the pattern of the regional climate or experiences any local anomalies. These were then combined with the SST and SSS data that was accessible via the National Oceanic and Atmospheric Administration (NOAA). The data was measured hourly by a GLOBAL-HYCOM remote sensor (available for the Farasan Islands (FARS1) at http://ecoforecast.coral.noaa.gov/index/0/FARS1/station-home). In this study temperatures are reported in °C and salinity in practical salinity units (psu), which is equivalent to parts per mil.

5.2.2 2012

In May 2012 a survey of the coastal landscape of the region was carried out as part of the DISPERSE project (Devés et al. 2013). In this context, it was possible to put two data loggers close to the Khotib-harbour on Saqid island (16.913982°N, 41.842615°E)

(Fig. 5.2), which were able to record the temperature and salinity of their surrounding water in 30 minute intervals. They were deposited at a depth of 1 m and 3 m to understand the differences between surface water and deeper water. The latter is less influenced by day/night temperature changes, short periods of rainfall or other anomalies. They were also put into hard plastic tubes, which protected them from any impacts by falling rocks and made it possible to tie the loggers onto heavier boulders to make them easier to find.

5.2.3 2013

In May 2013 the loggers were collected and their data was retrieved (Fig. 5.3). The loggers were covered by a thick layer of marine moss-like growth (probably alga or young sea grass) but showed no sign of being tampered with or having suffered any damage, nor did they show any signs of short interruption or longer times of non-functioning.

The recorded temperatures showed a maximum of 34.8ºC at the end of June 2012 and a minimum of 26.2ºC in February 2013. The year can be divided into three equally sized periods; a period of temperature rise, starting in February, a time of fairly constant temperature (around 33ºC) from June to October, and a decline in temperature from October to February.

While the data for temperature is realistic and expected, the salinity data is far too low for a Red Sea environment, which can experience values that are ten times higher (Bruckner et al. 2011). After a more thorough enquiry into the local environment, possible freshwater sources, and mistakes made by the configurations for the loggers, I found out that the equipment was not suitable for a highly-saline environment but only for the tracking of freshwater salinity changes. This is why the salinity data could not be gathered by myself but had to be replaced by data acquired through the National Oceanic and Atmospheric Administration (NOAA), whose measurements will be discussed below.

After the data loggers were configured to measure another year of temperature data, they were relocated to two different parts of the Farasan Islands to measure differences in local environments and compare open coastlines to more sheltered areas. Logger 6068 was put between the big islands Farasan Kabir and Saqid (Fig. 5.4), which is a very sheltered area with less water exchange. It was bound to a rock at the second pillar of a bridge also at a similar depth of 1.5 m. Logger 6069 was put into Janaba Bay, close to the JE0004 shell mound (Fig. 5.5), to get records from the place that was also being used to collect modern specimens of *C. fasciatus.* It was put under a concrete block of 30x30x50cm at the inshore border of the coral reef in about 1.5m depth. Additionally, the plastic protection, as well as both rocks, were painted with bright pink nail polish, to make them easy to find in the future.

5.2.4 2014

In March 2014 it was planned that both data loggers would be collected and their data retrieved. However, it was not possible to find logger 6068 again, which was located near the bridge between Farasan Kabir and Saqid. It is possible that a strong current moved the rock that the logger was tied onto far away from the bridge. However, it is also possible that a curious and inquisitive person or animal had removed it.

Logger 6069 had not moved and was easily recovered from under the concrete block at the Janaba Bay coral reef. The data was similar to the earlier recordings, with equal temperature measurements and similarly inadequate salinity measurements.

5.2.5 NOAA data

In addition to the local records from loggers 6068 and 6069, satellite data collected by the NOAA from 2010 to 2014 was used. Both datasets are very similar (Fig. 5.6). The exact location of the NOAA measurements is unknown. However, because the data from 2012 to 2013 is very similar, despite the two locations on different parts of the islands, it can be argued that the general temperature change is similar throughout the archipelago. The mean sea surface temperature has a maximum in August with 33°C on average, a range of 32.1–33.9°C. It reaches a minimum in March with an average of 27°C and a range of 26.5–28°C.

The NOAA satellite data also included measurements of salinity over a 4 year period. Water salinity reaches 38.8 psu in November. It decreases to 37.8 psu just at the end of the wet season in February/March and drops even lower from late April to early July to 36.9 psu. The salinity is partly influenced by the seasonal inflow from the Indian Ocean through the Bab al Mandab strait (Siddall et al. 2004, Trommer et al. 2010). This inflow is connected to a change in wind direction, which blows from the Southeast in October to April and from the Northwest in May to September. During times when the southerly winds prevail, less saline water from the Indian Ocean flows into the Red Sea on top of the high saline water. Simultaneously, high saline deep-sea water is being pushed out of the Red Sea by deep-sea currents. In the same way, the northerly winds drag surface water out of the Red Sea causing a subsurface inflow from the Gulf of Aden (Siddall et al. 2004). There are also times of almost no wind, when the general direction changes between the two periods. This sudden change can be the cause of heavy rainfalls, which, although they are intense, are not long-lasting. Heavy rain was witnessed in the field on 15 November 2012 (Fig. 5.7), which had no influence on the salinity of the marine water.

In conclusion, the sea surface temperature change throughout the year is significant and shows an overall range of about 7–8ºC. The change is regular and occurs at similar times of the year, with little variation between the different years or measurement locations. The seasonal salinity changes are equally comparable from one year to another. However, they have a much smaller range of only 2 psu. This small range can easily be explained by the lack of regular rainfall and general low precipitation throughout the year. As mentioned above, the southern Red Sea experiences a seasonal inflow from the south due to the wind coming from the Southeast from October to April. It is possible that this seasonal inflow causes less-saline surface water to flow into the marine environment of Farasan and causes a small change in salinity for the autumn and winter months. Considering all of this, the climatic conditions are suitable for stable ^{18}O isotope analysis because the change of isotopic composition of the marine water should chiefly be caused by the change in temperature and not be confounded by a change in salinity.

5.3 Marine water composition ($\delta^{18}O_W$ and δD)

The analysis of stable ^{18}O and ^{2}H (Deuterium, hereafter D) was carried out on marine water samples to provide a reference for the isotopic composition of the water that the mollusc grew in and to calculate the corresponding $\delta^{18}O_{est}$ in different seasons of the year.

Water samples (n = 19) from Janaba Bay and at eight sites around the archipelago were analysed in order to assess spatial differences and to explore the water exchange in different parts of the research area (Fig. 5.8, Table 5.1). The samples were put into 50 ml plastic vials with a screw top at ~50 cm water depth to avoid including any air bubbles that might introduce different isotopic values into the water. Stable isotope composition of seawater ($\delta^{18}O_W$ and δD) was measured at the British Geological Survey using the Gasbench and IsoPrime 100 plus aquaprep. The values are quoted relative to V-SMOW (Vienna-Standard Mean Ocean Water).

Site ID	Name	Date	$\delta^{18}O$ (VSMOW)	δD (VSMOW)
1	Seir	12.13	+1.67	+11.3
		9.13	+2.13	+12.0
		5.13	+1.41	
2	Seir-KM	12.13	+3.02	+16.6
		9.13	+2.52	+13.4
		5.13	+1.67	+14.6
3	Saqid	12.13	+2.34	+14.4
		12.13	+2.30	+14.7
		9.13	+2.13	+11.6
4	KM Bridge	12.13	+2.75	
		5.13	+1.75	
5	Janaba West	5.13	+1.55	
6	Janaba East	12.13	+1.94	+13.4
		9.13	+1.47	+8.7
		5.13	+1.22	
		2.13	+1.32	
7	SE Farasan kabir	12.13	+2.73	+16.9
		9.13	+2.22	+12.7
		5.13	+1.72	

Table 5.1 Results of $\delta^{18}OW$ and δD analysis

The stable ^{18}O isotope composition of the marine water at Farasan is fairly consistent but does show some seasonal changes (Fig. 5.9). The median value lies at +1.94 ‰, with a standard deviation of +0.5 ‰, a minimum value of +1.2 ‰ and a maximum value of +3.0 ‰.

The relationship between $\delta^{18}O_W$ and δD was analysed to gain insight into the overall humidity and to trace any evidence for water inflow from areas that experience different degrees of humidity, precipitation, and temperature (Clark and Fritz 1997). Because the salinity values from the NOAA record seem to coincide with the inflow of surface water from the Indian Ocean (Chapter 2.7.1), it is possible that this inflow has an influence on the stable isotope composition of the marine water around Farasan. This will eventually affect the stable isotope record of the shell, which is why it needs to be investigated.

Fig. 5.9 plots each sample with its corresponding $\delta^{18}O_W$ and δD value (blue dots). The gradient or steepness of the average line of the data points (dotted line) is then compared with the global meteoric water line (GMWL). The deviation from the GMWL indicates whether evaporation is a dominant factor in the fractionation processes, as is the case in arid environments, or if the water is exposed to more humid conditions. For example, water samples of more humid areas will show little deviation from the GMWL, which itself has a gradient of ~8. In contrast, areas with low humidity will have a gradient around ~4. The Farasan dataset has a gradient of 4.62 and is well within the range of arid environments. This is in agreement with the temperature and salinity data and subsequently it can be concluded that any significant inflow of water from different environments that would cause an anomaly in the stable isotope record can be ruled out.

Additionally, the stable ^{18}O isotope values from spring (May) and winter (December) were used to compare how different locations are being affected by evaporation (5.10). The spatial analysis was performed by the interpolation of stable $\delta^{18}O_W$

isotope data in ArcGIS. The sample locations were plotted on high-resolution satellite imagery and connected to a database with the corresponding stable isotope values. Subsequently, they were used to calculate a raster through an inverse-distance-to-power-method (IDW). This method estimates values between the sample locations in accordance with the values of nearby samples. The colouring of areas is arbitrary and the range is based on the minimum and maximum of the isotopic values that were used for the calculations (Site ID: 1,2,4,6). This isoscape is only preliminary and it can be significantly improved by adding more data from other areas to achieve a higher detail.

The May and December isoscapes differ significantly. While the May samples are more homogenous, the December samples show distinct differences in isotopic values between sites that are directly exposed to the Red Sea marine water and sites that are more enclosed. The enclosed sites experience less water exchange and are hence more susceptible to fractionation due to evaporation. Evaporation itself is increased during the summer with higher temperatures and no precipitation. This aspect of the spatial differences in isotopic composition around Farasan is especially important when comparing shell carbonate from archaeological sites that are not from the same areas. It is likely that the shells from enclosed sites experience a relative increase of $\delta^{18}O$ during the summer similar to the water samples above. This effect needs to be taken into account.

Of special importance to this study are the isotopic values of the water samples from Janaba Bay near the archaeological site JE0004. This is where the modern mollusc specimens were collected and the logger 6069 was located during 2013 and 2014. The $\delta^{18}O_W$ values (n = 6) from Janaba Bay exhibit little variation over the year, from +1.2 ‰ to +1.9 ‰ in May and December, respectively (average value = +1.5±0.3 ‰).

These values can now be used to calculate the stable isotope values that should occur in the *C. fasciatus* shell ($\delta^{18}O_{est}$). Solving equation 4.3 (Chapter 4.3) for $\delta^{18}O_{est}$ and using the $\delta^{18}O_W$ values from Janaba Bay and the daily mean temperature values (T) from the local loggers and the NOAA, it is possible to calculate the $\delta^{18}O_{est}$ throughout the year. Since there are no daily measurements of $\delta^{18}O_W$ the values needed to be interpolated for days between field seasons.

$$SST\ (^{\circ}C) = 20.6 - 4.34\ (\delta^{18}O_S - (\delta^{18}O_W - 0.27))\ \text{(Eq. 4.3)}$$

▼

$$\delta^{18}O_{est} = (20.6 - T\ (^{\circ}C) + 4.34\ (\delta^{18}O_W - 0.27))\ /\ 4.34\ \text{(Eq. 5.1)}$$

The resulting $\delta^{18}O_{est}$ values (Fig. 5.11) resemble the temperature change throughout the year. Following this, the changes in the stable isotope composition of the water are clearly dominated by the seasonal variation in temperature rather than changes in the salinity. Otherwise, the values for temperature and $\delta^{18}O_{est}$ would differ more significantly.

In conclusion, the stable isotope data from the marine water samples strengthen the assumption that no major influences from other water sources are present and that the change in temperature is the dominant factor that influences the $\delta^{18}O$ recorded in the shell carbonate. The overall isotopic landscape of Farasan reflects evaporation and surface water exchange with the surrounding Red Sea. However the marine environment of Janaba Bay, the main location of this study, is not significantly affected by fractionation resulting from evaporation and has sufficient exchange with the open water to avoid anomalies.

As a result of these findings the $\delta^{18}O_{est}$ dataset, based on the local environment of the *C. fasciatus* shell, can now be used to examine the shell carbonate as a proxy for palaeotemperature.

5.4 Comparison of $\delta^{18}O_{est}$ and $\delta^{18}O_S$ from shell edges

5.4.1 Introduction

After having presented the framework of environmental conditions of the marine landscape of Farasan, it is now possible to examine in more detail the results of the isotopic analysis of modern specimens of *C. fasciatus.*

The section will start with a description of the collection seasons and some of the problems that occurred. This is followed by the comparison of the estimated $\delta^{18}O$ values for collection days, and the values from edge samples ($\delta^{18}O_S$) that were collected on those days, to assess if they are correlated. In addition to this, the results of the $\delta^{13}C$ measurements will be presented, as well as their relationship to the estimated $\delta^{18}O$.

5.4.2 Shell collection

During every field season, modern specimens were collected. I tried to work together with the National Commission for Wildlife Conservation and Development (NCWCD) to collect shell and water samples on a monthly basis, which could then be sent to York. This arrangement would have made for a fuller dataset. However, this was not possible, thus the collection of shells happened about every 3 months. An additional problem was the localisation of live specimens. From earlier research (Bailey et. al 2013) it was known that the animal can be present in large numbers and groups of 50 have been seen on Soulayn Island, northeast of Farasan Kabir. In comparison, the area in front of the JE0004 shell mound is less rich in *C. fasciatus*. The reason why I chose this place as the main location for shell collection is the elusiveness of the mollusc in other areas of the Farasan Islands. Numerous fruitless expeditions have been carried out all around the islands, looking at different types of shorelines and micro-environments. Additionally, local fishers and members of the coast guard helped with these investigations, but this did not result in a better understanding of which habitat the mollusc prefers or where to consistently find it. Apart from the JE0004 location, only a beach north of the Seir village on Farasan kabir (also water sample location #1, Table 5.1, Figure 5.8), had *C. fasciatus* shell present. In contrast to what was previously known about the mollusc's preferred habitat (Sharabati 1984), namely, shallow, sandy bays that are sheltered from wave action, both sites were exposed to heavy wave action and had little to no sand cover over a rough coral bedrock. Both sites had some underwater vegetation, although this varied with the season. Summer months had very little vegetation (Fig. 5.12), while winter months had more extensive vegetation (Fig. 5.13). Additionally, the number of shells that were available to collect, experienced a worrying decline after the second collection in February 2013 (Table 5.2). The reason for this is unknown, but could be the overall mobility of the mollusc. The local population might have just migrated to another location.

Site	Date	n
JE0004	16.11.12	25
JE0004	01.02.13	18
JE0004	18.02.13	15
JE0004	25.02.13	10
JE0004	28.02.13	35
JE0004	30.05.13	10
JE0004	27.09.13	3
JE0004	27.09.13	2
JE0004	11.12.13	3
SEIR	30.05.13	6
SEIR	05.03.14	8

Table 5.2 Numbers of shells collected for transport to York

5.4.3 Shell edge values

The carbonate samples are all from the edges of juvenile shells, which were collected alive and immediately prepared for analysis by placing the animals in 5% NaClO. This secured an exact time of death. Samples remained in the solution for 48 hours. Afterwards they were rinsed and cleaned manually to remove body tissue. Samples were transported to the laboratory in York (BioArCh), where they were rinsed and sonicated with ultra-pure water, before being oven-dried at 40ºC. Subsequently they were sampled at the shell edge using a 0.9 mm drill bit on a hand-held Dremel drill.

Stable carbon and oxygen isotope analysis of the shell carbonate was performed at two laboratories, the stable isotope facilities at the University of Wyoming (USA) with a Thermo Gasbench coupled to a Thermo Delta Plus XL IRMS and at the isotope facilities of the British Geological Survey with an IsoPrime IRMS plus multiprep. Additionally both laboratories performed stable oxygen isotope analysis of water samples using a Gasbench and IsoPrime 100 plus aquaprep. This made it necessary to rerun some of the carbonate and water samples to compare results and verify that the data can be used and compared without adjusting for systematic biases. All values were reported in V-PDB and have a standard deviation of 0.04-0.06.

Collection Date	Average $\delta^{18}O_S$	Estimated SST	Daily SST	Month SST	$\delta^{18}O_W$	Daily SSS
16.11.12 n=2	-0.90	30.73	30.59	31.51	1.71	38.63
18.02.13 n=3	-0.56	27.95	27.69	27.17	1.40	37.87
28.02.13 n=2	-0.54	27.49	27.46	27.37	1.32	38.03
30.05.13 n=2	-1.55	31.47	32.10	31.11	1.22	37.73
28.09.13 n=5	-1.47	32.21	32.77	32.33	1.47	38.26
11.12.13 n=2	-0.67	30.76	29.72	30.47	1.94	38.39

Table 5.3 $\delta^{18}O_S$ values from shell edges of different seasons with the corresponding estimated temperatures based on seasonal values of $\delta^{18}O_W$.

Table 5.3 shows the values for all analysed shell edges (n = 16), the value for $\delta^{18}O_{est}$ and the temperatures on the day and month of collection (all modern stable isotope data is also available in Appendix 3). Shell-edge $\delta^{18}O_S$ values (n = 16) range from −0.5 ‰ to −1.7 ‰ ($\Delta^{18}O_S$ = 1.2 ‰) from the February (winter) and September (autumn) growth respectively. Using daily SST (NOAA) and corresponding $\delta^{18}O_W$, the predicted shell $\delta^{18}O_S$ (Eq. 5.1) shows a very good agreement with measured counterparts (R^2 = 0.88) revealing that *C. fasciatus* form the shells close to or in isotopic equilibrium with the ambient water (Fig. 5.14). The values only show one measurement with a questionable result (16.11.12). The reason for this is not known but could be contamination during the sample preparation.

In addition, the hypothetical temperatures based on the isotope composition of the shell carbonate were calculated using equation 4.3. The individual differences between hypothetical and actual temperatures only once (11.12.13: –1.04ºC) exceeded 1°C, which is a sufficient accuracy for palaeotemperature reconstruction.

Parallel to the $\delta^{18}O$ analysis, the stable $\delta^{13}C$ isotope composition was also measured. The $\delta^{13}C_S$ values vary between +0.62 ‰ and +2.07 ‰ ($\Delta^{13}C_S$ = 1.4 ‰). In contrast to the $\delta^{18}O_S$ values, which plot well in accordance with $\delta^{18}O_{est}$, the $\delta^{13}C_S$ values are negatively correlated to the $\delta^{18}O_{est}$ (Fig. 5.15). More specifically, they show a moderate positive correlation with SST ($R^2 = 0.52$) and a negative, correlation with $\delta^{18}O_S$ ($R^2 = -0.33$).

Whilst $\delta^{18}O_S$ oscillation can be associated with seasonal changes in SST and $\delta^{18}O_W$, interpretation of variations in $\delta^{13}C_S$ is much less straightforward (e.g. Andreasson et al. 1999; Gentry et al. 2008; Strauss et al., 2014). Changes in $\delta^{13}C_S$ have been linked to large salinity differences and changes in the $\delta^{13}C$ of dissolved inorganic carbon (DIC) (Gillikin et al. 2006, McConnaughey and Gillikin 2008, Mook and Tan 1991, Owen et al. 2008). Salinity changes are minimal in the study area (36.9–38.8 psu) due to the lack of freshwater drainage and the low levels of precipitation. The $\delta^{13}C_{DIC}$ variability could be the result of seasonal changes in photosynthesis. Phytoplankton biomass increases from October to April (e.g. Chlorophyll-a from 0.5 mg/m^3 to 3.5 mg/m^3) as a result of the monsoon-induced surface nutrient-rich water inflow from the Indian Ocean through the Gulf of Aden (Aiki et al. 2006; Raitsos et al. 2013). Additionally, during the summer, monsoon nutrient water is upwelled in the Gulf of Aden and ultimately transported into the Red Sea at an intermediate depth to eventually mix with the surface water in higher latitudes (Smeed 1997). During photosynthesis phytoplankton preferentially incorporate ^{12}C, which in turn enriches the DIC in ^{13}C

(Andreasson et al. 1999). However, this mechanism would result in an increase (decrease) of $\delta^{13}C_{DIC}$ in winter (summer) which conflicts with the $\delta^{13}C_S$ trend observed in those seasons (Fig. 5.15, Table 5.3).

An alternative explanation is that seasonal $\delta^{13}C_S$ variability, to some extent, reflects changes in food availability between warmer and colder months. *C. fasciatus* predominantly feeds on interstitial microflora and detritus (Taylor and Reid 1984) and although DIC may have a prevailing influence on the $\delta^{13}C_S$ values of *C. fasciatus*, increased feeding on phytoplankton during colder months may result in a larger contribution of metabolic carbon than of shell carbon (e.g. Chauvaud et al. 2011). This mechanism could be responsible for lower (higher) $\delta^{13}C_S$ values in colder (warmer) months. However to what degree the metabolic carbon contributes to $\delta^{13}C_S$ values in *C. fasciatus* is difficult to ascertain.

5.4.4 Summary

Shell-edge $\delta^{18}O_S$ values are very consistent between shells of the same season (Tab. 5.3) indicating that shell increments are created in isotopic equilibrium with the surrounding water and the shell can be used as a palaeotemperature-proxy. Their $\delta^{13}C_S$ values showed changes that could be attributed to an increase of phytoplankton but also small scale changes have been recorded in shorter sequences, which do not have a straightforward explanation. Additional work and a more detailed record of the phytoplankton populations in the southern Red Sea is needed to make better interpretations of this dataset.

5.5 Developing a method for sequential sampling of C. fasciatus

5.5.1 Introduction

After studying the environmental characteristics of Farasan in general and the Janaba Bay area in particular, and linking them to the shell edge samples of *C. fasciatus*, it was possible to analyse the growth of the shell throughout its life. This is important to develop a sequential sampling method with an appropriate sampling resolution to accurately define the season of death.

This section firstly starts with a description of the attempted growth study in the local environment, which is then followed by a more detailed section regarding the application of microscopic methods to define growth rates. Following this, the sequential $\delta^{18}O$ and $\delta^{13}C$ values from shells of different seasons is presented to assess different sampling resolutions on juvenile shells. The section concludes with the establishment of a sampling method for both parts (juvenile and adult) of the shell.

5.5.2 Local growth study

As mentioned earlier, the shell structure of *C. fasciatus* shells is not well known. Most assumptions are based on studies of other gastropods (Geary et al. 1992, Radermacher et al. 2009, Stoner et al. 2012). It was necessary to collect information on the growth rate to develop a sampling method and an appropriate sampling resolution for the stable isotope analysis of the shell. Otherwise, it would not be possible to know how much time is being recorded by a given amount of growth within the shell and the time scale of the results would remain unknown.

To solve this, a group of 50 *C. fasciatus* specimens were collected, measured and marked, before being put back into the water in November 2012. Collection took place at Janaba Bay in front of the JE0004 shell mound, measurements of length, width, and aperture size were taken with callipers, and molluscs were marked with a battery powered drill to roughen up the shell and then marked with a waterproof pen. After 5 hours in a water tank, the shells were put back into the same area where they had been collected. The idea was, that after three months the specimens, or as many of them as could be found, would be measured and then put back again. A similar method has previously been applied successfully by Mannino et al. (2008). However, after a test period of one day, only one specimen could be found again. Also, none of the other marked molluscs were found in any other collection period that followed. This could simply be due to the overall mobility of the mollusc, in combination with overall turbulence of Janaba Bay.

A second attempt was made in February 2013 with another 50 mollusc specimens prepared for a growth analysis using the same method. This second cohort was collected in Janaba Bay but transported to the uninhabited island Soulayn (N16.757602, E42.211703), which has previously shown the presence of large populations of *C. fasciatus* (Bailey et al. 2013). The underwater environment just off the Northwest beach of Soulayn is rich in vegetation and coral reefs. In between these reefs, one can find corridors with smaller plants and sheltered crevasses. The intersection of two corridors was selected to deposit the second cohort of molluscs. They were covered by a 5 x 5 m fishing net with a mesh made of nylon, and lead weights on the rim. Additionally, the net was tied onto large corals and weighed down by rocks as well as plastic bottles filled with sand and gravel.

When this location was revisited in May 2013, the net was covered with thick algae and ripped into various large pieces. The weights had remained in their places but none of the test specimens had stayed inside. None of the second cohort was found and the growth study was unable to be completed.

5.5.3 Growth increments

A more detailed analysis of the growth rates was carried out on specimens collected in February and May 2013. The specimens were prepared for sclerochronological examination using a method previously employed on oyster shells by Milner (2002). In this method a section of the shell is produced using 'Epothin' resin and a slow speed saw that make it possible to prepare a section of 10–25 μm thickness by grinding it with metallographic grid paper of increasing fineness. This can then be analysed under a microscope to get a detailed view of the growth structures.

Based on previous studies on *Strombus* shells (Geary et al. 1992, Stoner et al. 2012) I assumed there is a large difference between the growth rate in juvenile shell parts and adult shell parts because of the development of the thick lip when the animals reaches adulthood. However, the results for *C. fasciatus* were insufficient and it was not possible to consistently identify individual growth lines as they were not always visible under the microscope. Only in areas of shell growth with high amounts of brown pigments (carotenoids) could growth lines be made out (Fig. 5.16). When comparing the thickness of growth lines in pigmented areas of juvenile shells and the growth lines at the shell edge of adult shells, it is apparent that the latter are significantly thinner, indicating a slower growth rate. However, no actual comparison between lip parts and pigmented juvenile parts could be made, since the sequence of growth lines within pigmented areas is simply too short.

The shells lack those pigments in most areas, which is why staining to make the growth lines more visible was carried out on a small number of thin sections. The selected sections were rinsed in an ultrasound bath with ultrapure water and treated with Mutvei's solution for 20 min at 38–39ºC, based on the methods in Schöne et al. (2005). The results were partially successful and highly inconsistent. None of the shells showed clear growth lines throughout the sections. Again, the juvenile parts of shells might have grown too fast to actually show distinct growth increments. Only the lips of adult specimens were the areas with a high success rate as can be seen in specimen J4-3005-1 (Fig. 5.17). This could be due to a decline in growth rate and more distinct growth cessations. The structure of growth increments varies and even within one shell edge there are slightly different angles of growth direction.

Shell growth increments at the lip of J4-3005-1 range from 12.9 to 92.0 μm and display an average growth width of 38.1±18 μm. With increasing age, there is a general decrease of growth rate, which needs to be taken into account when looking for regular patterns throughout the record (Schöne 2003). This can be done by using the exponential trendline to predict the decrease in shell growth and then dividing the measured growth by the predicted growth, a method based on detrending in dendrochronology studies (Fritts 1976). Subsequently, the average of the difference between these detrended values is subtracted from each detrended value and then divided by the standard deviation.

This removes the age-related growth trend (Standardised Growth Index, SGI) and the frequency and the width of the increments reveal a pattern (Fig. 5.18). Further analysing the periodicity of those patterns (Fig. 5.19) through a wavelet power spectrum (Torrence and Compo 1998) shows a highly significant period of 14–17 days. This is consistent with daily fluctuations governed by fortnightly cycles that closely resemble the semidiurnal tidal regime (0.6 m) of the study area before the time of collection of J4-3005-1 (30.05.13).

This indicates that the growth lines are daily increments. The growth increments of this part of the shell provide us with an estimated growth rate of ~13 mm/yr. As mentioned before, this growth rate is only applicable to the shell edge of adult specimens. When, how and why the change in growth rate happens is not yet clear as the growth lines become less distinct in earlier growth increments of these shells.

5.5.4 Laser Induced Breakdown Spectroscopy

The use of Laser Induced Breakdown Spectroscopy (LIBS) is a laser ablation technique that has been shown to have significant potential in the use of environmental studies (Harmon et al. 2005, Marín-Roldán et al. 2014, Qiao et al. 2015). It produces spectra that represent the elemental composition of the analysed material (solid, liquid or gas). The method has the advantage of carrying out a multitude of measurements with a high spatial resolution and within a small time period. Additionally, it is in no need of sample preparation and works very cost-effective. In the context of this study, it was necessary to use the elemental composition of *C. fasciatus* shells to reconstruct the palaeotemperature. The high spatial resolution of the LIBS measurements can help to assess the temperature change that is recorded in the lip of an adult shell, thus providing another estimate of growth rate for this part of the shell.

Previous studies have shown that this relationship can be expressed through the Magnesium and Calcium ratio (Mg/Ca) in the carbonate (Ferguson et al. 2011, Finstad et al. 2013, Shirai et al. 2013). The ratio is expected to be positively correlated to temperature because the substitution of Mg into aragonite is an endothermic reaction (Rosenthal and Linsley 2006). Preliminary research on calcitic marine gastropods has produced promising results (García-Escárzaga et al. 2014). However, the results for aragonitic gastropods have been inconclusive.

Here, I present first results from LIBS measurements on modern *C. fasciatus* shells and assess how well the assumed temperature change correlates with the change that should be recorded within the time period suggested by the study of growth increments (~13 mm/year). However, due to the brevity of the study I only acknowledge these results and the potential future outcomes of the method. To fully make use of the method, more detailed analyses need to be carried out and additional factors that might influence the Mg/Ca ratio need to be ruled out (Poulain et al. 2015, Surge and Lohmann 2008, Wanamaker et al. 2008). A detailed description of the experimental setup used in this study can be found in Appendix 2. A brief description can be found in Fig. 5.20.

A modern shell (J4-3005-4) was prepared for analysis. The date of collection (30.05.13) is identical to the date of specimen J4-3005-1 that was used for the study of growth increments. The setup allowed to measure circular areas on the shell lip with a diameter of ~90 µm (Fig. 5.21). These dimensions allowed analysing the Mg/Ca ratio of the whole shell lip in 247 locations (Fig. 5.22) and tracking the change of the Mg/Ca ratio through time.

The results indicate that the elemental composition changes gradually from a lower Mg/Ca ratio to a higher ratio that is found at the edge. The total of the mapped data points show some inconsistency (especially at the edges of the sample) but the overall trend is compelling. The gradual change of Mg/Ca ratio could represent the temperature change towards warmer values from winter to spring until the date of harvest at the end of May.

This possible change in temperature recorded in ~2 mm of analysed shell could have happened over a few months, which is in agreement with the growth rate for adult lips as it has been found through the analysis of growth increments in the previous section (~13mm/year). Sadly, there is no reference for how the change in Mg/Ca ratio translates into temperature change. This means, that the gradual increase of Mg/Ca could have also happened over a few weeks and only resembles a decline of 1-2ºC. However, the gradual change in values sampled by small areas (~90µm) and the lack of hiatuses in the record suggest that there are no growth rates of the shell that are too slow. This suggests that increments that are too small to sample are unlikely.

5.5.5 Sequential stable isotope values

To get a better idea of the whole seasonal change represented by stable $\delta^{18}O$ and $\delta^{13}C$ isotopes and additional information about the growth rate of juvenile shells and juvenile parts of adult shells, longer and shorter sequences of carbonate samples were taken on each shell.

The following section explains the data produced from the carbonate analysis and discusses individual anomalies and possible explanations. The sequences are dealt with in the order of length and straightforwardness of the data. Only juvenile shells are discussed in this section. Accordingly, they were sampled using a 0.9 mm drill bit from the shell-edge towards the protoconch, following visible growth increments on the outer shell surface. Because no clear results were produced by the incremental study, I made use of different sample resolutions to find out about long term trends and short term variability, to eventually find a good compromise that is sufficient for the interpretation of the season of death.

The first analysed shell (J4-18-A, Fig. 5.23) was collected on 18th February 2013. Samples were taken along the outside of the shell with a sample width of in ~1 mm and a sample distance of 1 mm. Using many samples over a short distance allowed me to rule out that I missed any seasonal changes within the shell record. These changes could be very short summer or winter times when the shell grows slower or not at all because of extreme temperatures.

The $\delta^{18}O_S$ shell edge value is +0.51 ‰ and the overall trend of the ~ 40 mm record is a gradual decline to –1.5 ‰, a typical summer value. Following this, the recorded time could be 6 months (~ 80 mm/year) but this is far from conclusive. The record does not actually cover summer to winter distances as in seasonal minima and maxima and does not allow comprehensive estimations of growth rates. On the other hand, it shows that the sampling resolution of 1 mm samples with 1 mm distance is sufficient to track the seasonal change within the shell. Interestingly, along with the decrease in $\delta^{18}O_S$ there is an increase in $\delta^{13}C_S$ from +1 ‰ to around +1.5 ‰. In general the $\delta^{18}O_S$ and $\delta^{13}C_S$ values are positively correlated (R^2=0.37).

Two modern shells collected on 30th May 2013 (J4-3005-A; J4-3005-C) were used for a less detailed sequential isotope analysis with a sample size of 1 mm and a larger sampling distance of 2–3 mm. The shell edges of both specimens were slightly thicker than most juvenile shells, but did not yet have the distinct lip that is characteristic of adult shells. They were chosen because of this, as it is likely that they had almost reached adulthood and hence had the longest record of seasonal change that can be found in juvenile shells.

The results show sinusoidal $\delta^{18}O_S$ fluctuations reflecting seasonal SST changes over approximately one year's duration (Fig. 5.24). Shell J4-3005-A ranged from –0.6 ‰ to –2.8 ‰ ($\Delta^{18}O_S$ = 2.2 ‰) and shell J4-3005-C from –1.1 ‰ to –2.5 ‰ ($\Delta^{18}O_S$ = 1.4 ‰). The 80–85 mm sequence of values provides a record of environmental conditions (e.g. $\delta^{18}O_W$ and SST) over approximately one year, suggesting a fast growth rate (~80 mm/yr). When comparing both lines, it appears that the growth was not always similar and that shell J4-3005-C grew faster than J4-3005-A in the area between 0 and 60 mm from the shell edge.

Also, the isotopic range of J4-3005-A is much smaller than its counterpart, as it does not reach values above –1 ‰ in the 10–30 mm area from the shell edge. The values in the youngest part of the shell are similar to J4-3005-A and the edge samples are almost identical. Since both shells were collected almost next to each other, it is possible that the similarity of the shell edge values is due to the shells sharing the same microhabitat. The short-lived difference in $\delta^{18}O_S$ values throughout winter could have been caused by one of them migrating somewhere else, or both migrating into different places with different $\delta^{18}O_W$ values. Earlier chapters have shown the variation in $\delta^{18}O_W$ throughout Farasan and the mobility of the shells has been demonstrated above by the failure to recover the live shells collected and marked for the control studies of growth. The possibility of microhabitats that are visited and then left by the molluscs and the effects this can have on the stable isotope record in the shells needs to be factored into the analysis. There is also the possibility that there is a sexual dimorphism that is not accounted for. The female specimens of some strombid shells can be slightly larger (Walls 1980), which will also affect the growth rate in shells.

Sequential $\delta^{13}C_S$ values range from +0.2 ‰ to +2.7 ‰ ($\Delta^{13}C_S$ = 2.5 ‰) and +0.4 ‰ to +1.6 ‰ ($\Delta^{13}C_S$ = 1.2 ‰) respectively (Fig. 5.5.4). Intra-shell $\delta^{13}C_S$ and $\delta^{18}O_S$ values are again negatively correlated in J4-3005-A (R^2 = –0.33). No similar correlation was found in J4-3005-C (R^2 = 0.07), which is mostly due to the inconsistency of $\delta^{13}C_S$ values that are further than 40 mm away from the shell edge. If these values were similarly consistent as the ones in J4-3005-A the overall negative correlation would be much more significant.

It is unclear whether the inconsistencies are again because of microenvironmental variation that influences the isotope composition of the shell. However, if the food intake is indeed the main control on $\delta^{13}C$, then this could explain the simultaneous decrease of $\delta^{13}C$ values in winter. What happens before then (+40 mm) is unclear.

Two shells that were collected on 13th December 2013 were analysed, with growth sequences covering 83 mm (J4-123-A) (Fig. 5.25) and 70mm (J4-123-B) (Fig. 5.26). As was the case for J4-3005-A and J4-3005-C, the sequences cover the increments from the shell edge to the protoconch. But despite the similar length of the sampled areas, the shells do not seem to be of the same age. For both shells the edge values (–0.75 ‰ for A and –0.74 ‰ for B) are close to what would be expected for the season. Also, the trend towards lower values is in accordance with the estimated trend to lower values in summer. However, whereas J4-3005-A and J4-3005-C show the various values of several seasons within 80 mm of growth increments, J4-123-A and J4-123-B only show two seasons, meaning that they grew much faster than J4-3005-A and J4-3005-C. It could be argued that the flatness of the curve is the result of time averaging. This happens when the sampling resolution is too low in relation to the growth rate, so that extremely negative and extremely positive values are mixed together and cancel each other out. Luckily, this effect can be ruled out, because each sample only covers a growth of ~2 mm, and it would be necessary to have high and low extremes in the same sample to result in the averaging of their values. I argue that it is more likely that the shell grew almost twice as fast as J4-3005-A and J4-3005-C, rather than growing so slowly that summer and winter have been merged into growth increments of ~2 mm thickness.

The $\delta^{13}C_S$ values (1.54 for A and 1.51 for B) and both curves follow roughly the same trends. J4-123-A has a slightly longer record, but seems to cover the same amount of time and simply grow a bit faster than J4-123-B. Both show a trough $\delta^{13}C_S$ at 10 mm distance from the edge. Shell B has a slightly bigger peak, despite its lower growth rate. In contrast, a second trough with lower values at ~60 mm is more pronounced in shell A.

It is clear that the growth rate in *C. fasciatus* shells is not just different from one individual to another, but can also change within one specimen with times of fast growth and times of slow growth, without any clear controlling factor.

The shells J4-16-A and J4-16-C were collected on 16th November 2012 (Fig. 5.27 + 5.28). Shells A and C are both similar to the shells from December of the following year (J4-123-A and J4-123-B) but each in their own ways. With an edge value of –0.5 ‰ and an overall trend towards summer values just below -1.5 ‰, J4-16-A is very much the same as J4-123-A and J4-123-B. Also in terms of growth rate, it follows the trend of a more rapid growth. In comparison the edge $\delta^{18}O_S$ value of J4-16-C is lower (–1.2 ‰) and the values for summer almost reach –2 ‰. It is less likely that this is the result of different micro-environments with different conditions as both shells have been found in the same place. Interestingly, the short negative peak in $\delta^{13}C_S$ at the end of summer that has been found in J4-123-A and J4-123-B, also appears in J4-16-C. It is simply a bit closer to the edge in J4-16-C, which is expected, given the 1-month seasonal difference. Overall, the $\delta^{13}C_S$ of both shells from November follow the trend of increased values in the summer.

The last set of shell edge sequences consists of three sequences (J4-289-A, J4-289-B, J4-289-C) from very young shells collected on 28th September 2013 (Fig. 5.29-29). They were part of a group of 5 small shells (25 mm or less in length). For reasons unknown, no older shells were found during that collection period.

All three shells follow the same trends with $\delta^{18}O$ being fairly stable with a value of –1.5‰ and with $\delta^{13}C$ showing a downwards trend from +2.0 ‰ to +1.2 ‰. The $\delta^{13}C_S$ of shells B and C are similar as they both have a small bump in their overall downwards trend (Fig. 5.30 + 5.31). However their $\delta^{18}O_S$ values are not equally similar. On the contrary, the $\delta^{18}O$ of J4-289-C resembles much more the sequence of J4-289-A (Fig. 5.29). In both cases of similarities the fluctuations within the sequences, despite being almost parallel in some parts (J4-289-A and J4-289-C between 10 and 20 mm), are comparatively small (±0.4 ‰). This minimal change in the record has to be seen in context with the overall small period of time that is covered by the sampled area due to the shell's young age. This is combined with the limited change in isotopic composition during summer (Fig. 5.3.4). Therefore, these minimal changes are likely to be caused by an unknown factor which occurs on a much smaller time scale than seasonal factors, and this cannot be tracked with short sample sequences such as these (>20 mm).

It could be argued that shell J4-289-B does show an upward trend of $\delta^{18}O$ towards the end of the sampled area. However, it is doubtful that this upward trend is the onset of the spring period with colder temperatures and that seasonal change was visible within this short sequence because the sample distances from the shell edge are too small (10–16 mm) and the overall growth rate in the previously discussed shells is much higher (>80 mm/year).

The three sequences above show that when sampling juvenile shells or juvenile parts of shells to record seasonal change it is important to cover a longer sequence of growth increments and acquire sequences of at least half a year (>40 mm).

5.5.6 Summary and sampling methods

Growth increments on adult shell edges that were treated with Mutvei's Solution showed growth patterns that were aligned with tidal fluctuations within the area. This indicated a growth rate of ~13 mm per year in that part of the shell. A conclusive assessment of growth rates within the juvenile part of shells could not be achieved through microscopic studies.

Stable isotope analysis showed that the employed sampling strategy provided enough resolution for tracking short-term SST changes provided that the sequences were long enough (>40 mm in juvenile shells). The growth rate in juvenile parts of the shell is somewhat unclear and seems to vary between each individual shell. The fact that two shells can been found at the same time and show similar seasonal curves, while being very dissimilar from other shells that live in the same marine environment, is leaving a number of unanswered questions. However, a general growth rate of ~85 mm/year is likely. The dissimilarities between shells may have to do with their mobility and specific microenvironments. This was very visible in the comparison of the stable $\delta^{13}C$ isotope values for the two shells with long sequences (J4-3005-A and J4-3005-C). Additionally, more information on the mobility and habits of *C. fasciatus* is needed to account for or rule out the effects of microenvironmental differences as a cause of anomalies in the stable $\delta^{18}O$ and $\delta^{13}C$ record.

The two growth rates of ~13 mm/year and ~85 mm/year make it necessary to sample each part with a different method. Hence the ideal methods for stable isotope analysis are a low-resolution method for juvenile parts of the shell and a high-resolution method for the lips on adult shell edges. The low resolution method involves cleaning the samples in ultra-pure water, subsequent sonication and drying at 40ºC. After this the shells are sampled with a 0.9 mm drill on the shell edge as well as along the outside of the shell following the whorl at a 2-3 mm distance between samples (Fig. 5.32).

The high-resolution method on adult *C. fasciatus* shells involves the same techniques for cleaning the shells but following this a thick-section is created that contains the lip part and the most recent growth increments. The shells are cut perpendicular to the growth lines and mounted on glass slides using epoxy resin (Araldite rapid epoxy). Then, they are cut again parallel and at a 3 mm distance to the slide and are subsequently polished with metallographic grid paper (P800, P1250, P2500). Then, they are cleaned and sonicated again with ultra-pure water and dried overnight. Afterwards, a photo is taken with a Zeiss AXIOScope microscope. This is done to document the lip's structure and check for hiatuses or indicative growth increments before sampling the lip. I used a 0.4 mm drill bit on a fixed Dremel drill that is lowered via a lever for a precise and controlled sampling process. The sampled area is ~0.4 mm in diameter and the sample distance is between 0 and 0.5 mm. Sequences of 10 to 20 samples are taken along the direction of growth for the whole lip (Fig 5.33).

I decided on a comparatively long sequence in comparison to other seasonality studies to account for changes that one can expect in growth rate and shell structure as the shell increases in age and size. Because I do not have detailed biological records for growth rates in *C. fasciatus*, I need to be able to assess what is recorded in the shell rather than basing my interpretation on prior knowledge of shell growth.

I argue that following the above technique for adult and juvenile shell sections has a sufficiently high resolution for sampling for seasonal $\delta^{18}O$ changes in *C. fasciatus*, given what little we know about its growth characteristics. I will explore the issues regarding the changes in growth rate and growth hiatuses in more detail in the following chapter, where I focus on the analysis of $\delta^{18}O$ sequences using statistical analyses.

5.6 Chapter summary

This chapter aimed to describe the data gathered in the 2012 to 2014 field seasons and the analysis of the stable $\delta^{18}O$ and $\delta^{13}C$ isotope measurements carried out on carbonate from modern shells. The data of local temperature loggers as well as the data from the NOAA showed a seasonal change in temperature and minimal change in salinity. The analysis of water samples collected in different areas around Farasan showed little change in the stable $\delta^{18}O$ and δD isotope composition of the water. It also showed that the isotope composition is more affected by evaporation processes than by the influx of less saline water from precipitation, from riverine systems, or from marine water inflow from the Indian Ocean.

It was possible to show that modern *C. fasciatus* precipitate their shells close to equilibrium with the oxygen isotope composition of the surrounding seawater at a given temperature according to the palaeotemperature equation of Grossman and Ku

(1986). Over an annual cycle the $\delta^{18}O$ from *C. fasciatus* records the full seasonal range of SST without apparent growth hiatuses. It was also possible to show that *C. fasciatus* reaches maturity (with continual growth) in about a year, with the shell growing very fast in the first year (~85 mm/year). Then there is a considerable decrease in growth rate on reaching adulthood when the lip thickens (~13 mm/year). It is also shown that both growth rates are sufficiently fast to avoid time averaging and can be used as a reliable proxy for seasonality studies. This was also confirmed by the gradual change of temperature represented by the Mg/Ca values from small sample areas (~90 μm) that did not indicate any growth rates that would be too small to sample.

It was shown that $\delta^{13}C$ could be a function of food availability and changing $\delta^{13}C_{DIC}$ of seawater in the region, which can be used as another seasonal proxy. Interestingly, both $\delta^{18}O$ and $\delta^{13}C$ records showed small-scale anomalies that do not make it impossible to assign a season of death but could cause problems in sequences that are less clear to analyse. How I decided to account for these anomalies and assess inconsistencies in the analysis of seasonality data, will be discussed in the next chapter.

Chapter Six

Statistical evaluation of shell edge sequences

6.1 Introduction

The previous chapter showed that the analysis of stable $\delta^{18}O$ isotope from shell carbonate of modern *C. fasciatus* shells produces valid results for reconstructing palaeotemperature. As the dominant species in the layers of JW1727 *C. fasciatus* will also produce a representative result for the seasonality of the site. However, the uncertainties of shell growth and general behaviour of the animal will hinder a comprehensive interpretation of the shell edge sequences. The modern sequential data has shown that there are differences in growth rates in shells of similar ages (Chapter 5.5.5). Also the general enrichment in ^{18}O isotopes can vary from one specimen to another (see comparison of J4-3005-A and J4-3005-C Fig. 5.24). This can make it difficult to accurately determine the season of death if there are no minima and maxima present in the shell edge sequence. If the visibility of growth increments within the shell were consistent enough to be used to assess the length of time recorded or to show seasonal growth patterns, the analysis of increments could help to target the minima and maxima that are recorded in the sequential isotope values and assess the general growth rate (Burchell et al. 2013). This would help to counteract these unknowns. Sadly, this is not the case.

The lack of visibility means that it is only possible to interpret the sequential isotope values as they are and without any reference to the time recorded in the sampled growth increments. For this, the changes in the overall curve need to fit to the changes that we would expect to happen in the shell record depending on what is known from the growth rate and the general climate. This does not just include the overall range of stable isotope values but also the consistency of the data. The consistency needs to be high enough to guarantee that the overall seasonal change is not affected by outliers or other anomalies in the record. Only then can we make a confident seasonal interpretation based on the isotopic changes that we seen in the last growth increments.

To make this interpretation as objective as possible and to support the determination of the seasonal signal at the end of the isotopic sequence, I developed a statistical evaluation of the dataset. How I did this, and how it influences my interpretation of the seasonality of JW1727 will be the subject of this chapter.

The first section of this chapter will give a description of the theoretical framework and the development of the method (**Chapter 6.2**). This is then followed by an overview of the different degrees of confidence that were found for the interpretation of stable isotope sequences (**Chapter 6.3**). Following this, I compare characteristic growth increments in the shells with the corresponding isotope data to make assumptions of how one can assess the quality of the stable isotope sequence based on the growth increments (**Chapter 6.4**). The chapter concludes with a discussion of the method in comparison with other approaches and a discussion of the necessity for statistics to increase the validity of interpretations in seasonality studies (**Chapter 6.5**).

6.2 Building a reference curve for seasonal change

6.2.1 Theoretical framework

Depending on the various growth rates between specimens, environmental and metabolic influences, as well as general irregularities, the sequential stable isotope data will be harder or easier to interpret. This will result in the season of death being more or less easy to determine. Unfortunately, many of the above factors are unknown for *C. fasciatus* and were not possible to further analyse during the modern study. However, an objective statistical evaluation can assist in this situation.

The use of $\delta^{18}O$ values from unknown mollusc species (similar to *C. fasciatus*) is a common problem in palaeontology, as many analysed species do not exist in the modern world and a modern reference is difficult to find. Wilkinson and Ivany (2002; see also Ivany et al. 2000) find ways to extract valuable information about growth rates and environmental change from $\delta^{18}O$ sequences. To better estimate annual means and seasonal ranges based on $\delta^{18}O$ from shell carbonate they developed a computational approach that addresses the uncertainties in the creation of shell carbonate. For this, they analyse a group of data points within a certain window to define the best fitting sinusoidal curve for this part of the sequence. While the window moves along the curve, changes in growth rate and seasonality are being picked up and can be compared to other positions in the sequence but also other sequences in general. This gives a far better understanding of climatic changes than simply visually assessing the seasonal changes. Even more so, as information about the animal itself can be revealed and anomalies in the $\delta^{18}O$ record can be explained. For example, Ivany et al. use $\delta^{18}O$ values to statistically measure changes in growth rate and duration of shell growth.

These estimations are obviously meant to help in the assessment of fossil organisms, but they are just as necessary when determining the season of death in known organisms, because as shown previously (Chapter 5) variabilities exist and an evaluation of the robustness of the dataset is needed.

Following the statistical approach above, I develop a new method that is intended to statistically evaluate the quality of the stable isotope data from archaeological shells and the suitability for providing reliable estimates for seasonality. More specifically, the method measures the data's capability to construct a seasonal curve that matches the seasonal change recorded in the modern environment. The objective here is to explore the probability that sequential isotope data predominately reflects temperature change, and to assess the impact of anomalous isotope values which are possibly derived from other factors. This assessment is crucial when working with shell carbonate derived from shells whose internal processes are not well known and in an environment that is equally unexplored.

As a basic seasonal reference I used a hypothetical curve that describes a sine curve (Fig. 6.1) with (a) describing the semi-amplitude of the seasonal curve, (b) the period, (c) the phase shift along the x-axis and (d) the position along the y-axis (Eq. 6.1).

$$y=a*\sin(b*x+c)+d \qquad \text{(Eq. 6.1)}$$

In this example the amplitude (a) would be controlled by the overall temperature change and corresponding range of $\delta^{18}O$ recorded in the shell. The period (b) depends on the growth rate throughout the year. A quickly growing shell will have a lower value and a slowly growing shell will have a higher value. The phase shift (c) or the position along the x-axis describes at what season of the year the curve intersects with the y-axis (start of sequence, time of death). The position along the y-axis (d) is dependent on the general enrichment or depletion in $\delta^{18}O$ as it sets the centre of the curve higher or lower.

This basic sine curve needs to be adjusted to fit the expected seasonality pattern in the modern shells, using a least squares analysis. I achieved this by using the statistical program R and its ability to carry out a least-squares analysis of non-linear equations (nls-function). The program is widely known and openly available under (http://www.r-project.org/). Least-square is an analytical method that is popular for data-fitting. It finds the best fitting curve to a specific set of data points by keeping the sum of the squared residuals as low as possible. In this study the residuals are the difference between observed values ($\delta^{18}O$ value at specific times of the year) and the constructed values. Ideally the constructed curve goes through all points and each squared residual is 0.

In the following I will present several uses of the nls-function in R. The program uses a console for the input of data and commands via text. I present this input in the form of text with a grey background (`R-commands`). This will allow my analyses to be reproducible by copying the text within the grey area into the R-console. The results of the analysis will be presented in graphs and in boxes with tables where applicable.

To carry out a successful least-square analysis R needs starting points for the parameters (a,b,c,d) in the equation above as a reference and to prevent it from calculating fits that are unrealistic. I derived these points from the shell sequence of J4-3005-B from the modern control study, as it has the best fit with the NOAA data and our own data loggers. It is also one of the few sequences with a complete all-year record, which can be used to estimate the growth rate. Because J4-3005-B is a juvenile shell, whereas almost all shells from the archaeological record are adult, the length of the sequence needs to be shrunk from a one year growth of 80 mm to a one year growth of 13 mm/year (5.5.5), so the results can be applied to shell edges from adult shells. After adjusting the value for the distance to the shell edge for each $\delta^{18}O$ value, I plotted the sequence in R using the following commands.

First I defined the x and y values for the scatterplot. In this command "xshellb" is defined as each sample distance from the shell edge in mm (adjusted for 13mm/year growth rate) and "yshellb" is defined as the sequence of $\delta^{18}O$ values in ‰VPDB. Note that “c” is a function within the program and is not equivalent to the “c” in Equation 6.1.

```
xshellb=c(0.00, 0.16, 0.32, 0.37, 0.81, 1.30, 1.70, 1.95,
2.16, 2.43, 2.57, 2.86, 3.23, 3.57, 4.06, 4.16, 4.52, 4.87,
4.91, 5.27, 5.71, 6.20, 6.75, 7.31, 7.94, 8.50, 9.02, 9.46,
9.93, 10.47, 10.82, 11.13, 11.36, 11.78, 12.25, 12.70, 13.00)
```

```
yshellb=c(-1.20, -1.49, -1.37, -1.50, -0.75, -0.80, -0.60, -
0.75, -0.70, -1.07, -1.20, -0.70, -0.60, -0.84, -0.76, -0.80,
-1.10, -0.88, -1.30, -1.10, -1.40, -1.70, -1.90, -2.10, -
2.10, -1.90, -2.60, -2.30, -2.10, -1.80, -1.80, -2.80, -2.10,
-1.90, -2.20, -1.90, -1.40)
```

Then I created the scatterplot for the above values. The function in R is “plot”, the parameters “ylim” and ”xlim” define the displayed area of the plot on the y-axis and x-axis, “type="o"” tells R to connect the points with a line, the remaining commands are axis descriptions.

```
plot(xshellb, yshellb, ylim=c(-3,0), xlim=c(0,13), type="o",
main="Sample curve", xlab="Distance from shell edge [mm]",
ylab = expression(paste("δ"^18*"O"*" (‰) VPDB")))
```

The result can be seen in Fig. 6.2.

Before the first least-square analysis can be carried out it is necessary to give the analysis some starting points, whereby it can generate accurate parameters (a,b,c,d) for Equation 6.1. From the results of J4-3005-B I was able to deduce several parameters to use as these starting points.

For (a) I chose the value 1 as the semi-amplitude is approximately 1‰. For (c) it is not necessary to define a starting point, because it has no real influence on the curve, but only moves it along the x-axis. For (d) I used the value -1.5 because the centre of the curve can clearly be seen in the graph. The period (b) was more difficult to ascertain. Based on the growth increments (Chapter 5.5), the period of the graph is derived from the growth rate of 13 mm/year. This information allows me to calculate (b) as it is usually the equivalent of 2*π/(distance between peaks, here 13mm).

This can be calculated in R,

```
b=2*pi/13
```

and results in b=0.48

With the starting points given, I carried out a first least-square analysis, which provided more accurate values for the sine-curve parameters (a,b,c,d). The function in R is called nls (non-linear least squares analysis) and for sine curves it looks like this:

```
nls(y~a*sin(b*x+c)+d, start=list(a=a, b=b, c=c, d=d)
```

I defined the function “fit”, which can then be used in other commands for subsequent analyses. Together with the starting points it can be put into the R console.

```
fit=nls(yshellb~a*sin(b*xshellb+c)+d, start=list(a=1, b=0.48,
c=0, d=-1.5))
```

To see the results, I used the summary-function and the name “fit” for the analysis.

```
summary(fit)
```

The result can be seen in Table 6.1.

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
a	0.77030	0.06267	12.291	7.29e-14 ***
b	0.45383	0.01922	-23.615	< 2e-16 ***
c	0.30607	0.14006	-2.185	0.0361 *
d	-1.55096	0.04341	-35.725	< 2e-16 ***
Residual standard error: 0.2575				

Table 6.1 Results of least square analysis for the adjusted shell edge samples of J4-3005-B.

Least-square-analysis found new, more accurate values for the sine-curve parameters (a,b,c,d). The value (a) changed from 1 to 0.77, the value (b) changed from 0.5 to 0.45, the value (c) became 0.3 and the value (d) changed from -1.5 to -1.55. These new values are fairly close to the estimates of the starting points.

Looking at the other data in Table 6.1, we can see that the standard error of three of the parameters (a,b,d) is fairly low, while for (c) it is higher. This means that the derived values for the parameters fit well to the complete dataset, except that it was difficult to fit a value for (c) that fits the whole dataset. R carries out a t-test for the significance of each parameter, which can give some indication of the quality of the fit. Here it is not necessary to take this t-test into account, as I am more interested in the residuals that were created and how well they fit to the estimated curve. This example has a residual standard error of 0.26. This error is most likely due to the variability of values at the end of the sequence (8-12 mm from shell edge). How the new curve fits to the dataset is shown in Fig. 6.3.

To plot the most likely seasonal change with the new parameters, I used the lines-function, for plotting lines, and a sequence (`seq`) of x-values distributed over the 13 mm displayed in the graph for every 0.1 mm within it (`xyear`). These will produce a smoother sine curve, than the more sparse x-values of shell J4-3005-B.

```
xyear=seq(from=0,to=13,by=0.1)

lines(xyear,0.77*sin(0.45*xyear+0.3)-1.55, col=c("blue"))
```

Following this, the resulting ideal curve for the modern reference data is:

$$f(x)= 0.77 * \sin(0.45 *x) – 1.55 \qquad \text{(Eq. 6.2)}$$

This curve can now be used as a reference for shell edge sequences. In the following, I will test it on another shell edge sequence of known season of death.

6.2.2 Applying the analysis to shorter shell edge samples to assess the seasonal signal

The sequential data from the modern shell J4-18-A will be used as an example. The shell was collected on 18.02.2013 and has the highest sample resolution in the dataset. A sequence of 39 carbonate samples was collected. The samples covered a time span of only about 6 months based on the isotopic change.

With the modern $\delta^{18}O$ curve as a reference it was possible to measure how well the data points from J4-18-A fit to the seasonal change. Similar to the previous section a sine curve was created and fitted to the data points of J4-18-A, using least square analysis and the parameters of the ideal curve as starting points. The extent to which the parameters need to change during the analysis and how well the data fit to the curve afterwards will give insight into the seasonal character of the sequence and how it differs from the 13 mm/year growth rate measured in the growth increments.

Again, the x and y values are being defined for J4-18-A and the analyses called “fit” resulting in a table with the statistical data for each parameter (Table 6.2).

```
x18a= c(0.16, 0.28, 0.44, 0.60, 0.80, 1.03, 1.24, 1.34, 1.47,
1.62, 1.78, 1.91, 2.06, 2.25, 2.43, 2.62, 2.75, 2.93, 3.13,
3.29, 3.41, 3.58, 3.75, 3.92, 4.11, 4.29, 4.42, 4.54, 4.67,
4.84, 4.99, 5.15, 5.35, 5.49, 5.66, 5.85, 5.85)
```

```
y18a=c(-0.51, -0.64, -0.50, -0.93, -0.60, -0.65, -0.85, -
0.77, -0.86, -0.89, -0.95, -0.94, -1.02, -1.04, -1.02, -0.77,
-0.99, -1.15, -1.26, -1.13, -1.25, -1.22, -1.16, -1.43, -
1.38, -1.59, -1.36, -1.43, -1.51, -1.47, -1.55, -1.43, -1.28,
-1.38, -1.41, -1.33, -1.30)
```

```
fit=nls(y18a~a*sin(b*x18a+c)+d,  start=list(a=0.77,  b=0.45,
c=0.3, d=-1.55))
summary(fit)
```

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
a	0.40856	0.04781	8.545	7.10e-10
b	0.60026	0.10255	5.853	1.49e-16
c	1.72278	0.40034	4.303	0.000141
d	-1.01249	0.05446	-18.593	< 2e-16
Residual standard error: 0.1104				

Table 6.2, Results of least square analysis for the adjusted shell edge samples of J4-18-A. New parameters are fairly similar to the ideal curve. Note the smaller amplitude and higher value for (d).

The four parameters have changed (a=0.41, b=0.60, c=1.7, d=–1.01) and the resulting sine curve can be calculated accordingly (Fig. 6.4). Note that I used the value for (c) from the new curve (c=+1.7) for drawing both curves, so they are aligned.

```
plot(x18a, y18a, ylim=c(-3,0), xlim=c(0,13), type="o", main="Sample curve", xlab="Distance from shell edge [mm]", ylab = expression(paste("δ"^18*"O"*" (‰) VPDB")))

lines(xyear,0.4*sin(0.6*xyear+1.7)-1.01, col=c("blue"))

lines(xyear,0.77*sin(0.45*xyear+1.7)-1.55, col=c("black"))
```

The new curve is similar to the reference curve (black), but also shows distinct differences. The least-square analysis found new parameters for a growth rate of J4-18-A. The shell is more likely to have been growing slower than J4-3005-B. It is also found to be generally more enriched in $\delta^{18}O$ (d'=–1.01), a prediction most likely based on the less sloping end of the sequence at 4-6 mm, indicating a minimum in the curve with a following upwards trend. Also the amplitude is smaller, as there is a smaller range of isotope values found within the sequence. The residual standard error is much lower than in J4-3005-B. This means that regardless of what the curve looks like the data points do not deviate far from it, meaning that the sequence in itself is very coherent. This is also expressed in the small residual standard error (0.1104). To get a better look at the distribution of residuals, I used the residual-function (`resid`) and created a boxplot (`boxplot`) of them (Fig. 6.5).

```
boxplot(summary(resid(fit)), ylim=c(-1.5,1.5), main="Range of
residuals", ylab = expression(paste("δ"^18*"O"*" (‰) VPDB")))
```

The residuals are fairly small with most of them between 0.1 ‰ and -0.1‰ relative to the estimated curve values. There are two distinct outliers with –0.3 ‰ and +0.4 ‰. These outliers can also be seen in the plot (Fig. 6.4) at 1 mm and 3 mm distance to the shell edge. The mean of residuals (`mean`) is close to 0 ‰ and the interquartile range (25th–75th percentile) (`IQR`) at 0.12 ‰.

```
mean(residuals(fit))
IQR(residuals(fit))
```

What does this mean for the interpretation of the shell edge sequence? Following this example, I argue that generally the range of residuals should be similar to the error that I should apply to the last point of the sequence at the shell edge. If the majority of the values are within a range of 0.1 ‰ to the estimated seasonal curve, then the terminal value should not deviate more than 0.1 ‰. In this example it does not. If it did, the value would be suspicious as it would not fit to the general trend of the curve.

For the interpretation of the shell edge sequence and its seasonal signal this means that based on the little deviation of the overall sequence from the seasonal curve, the terminal shell edge value is not likely to be an anomaly but has a high probability to represent the actual season of death.

However, there are problems with the actual season that the estimated curve ends with (i.e. crosses the y-axis) and has likely to do with the smaller amplitude of the estimated seasonal curve. This problem needs readjusting, which will be the subject of the next section.

6.2.3 Necessary adjustments

When comparing the two curves from previous sections, the estimated amplitudes vary (in J4-18-A a=0.41, in J4-3005-B a=0.77). R assumes that the isotopic range of the sequence is equal to the seasonal range in temperature that the mollusc experiences. Following this, the highest value in the dataset will always be estimated as a winter temperature, which is incorrect. Even though there is a good chance of the J4-18-A sequence representing the lower values of the seasonal isotopic range at 4-6 mm (Fig. 6.4), it is uncertain if it also represents the higher values of the range at 0-2 mm which is what the least-squares-analysis proposes by indicating that –0.5 ‰ is the yearly maximum. There is no record of this maximum and it would be wrong to extrapolate it without additional data. Wrongly, R expects the modelled seasonal curve to use the isotopic range represented by the shell edge sequence, a preconception which can result in amplitudes much lower than what would be expected for the isotopic range. Every sequence that ends on a sloping trend, indicating a spring or autumn season of death, would be interpreted as having reached the end of the isotopic range and thus having ended at minimum or maximum part of the curve.

To prevent this, I predefined the amplitude using the results of the $\delta^{18}O_{est}$ based on $\delta^{18}O_W$ from modern water samples and temperature measurements by the NOAA and my local loggers (Chapter 5.3, Fig. 5.11). Accordingly, for future analysis the parameter for the amplitude (a) is a=0.77. This value is also in accordance to the shell J4-3005-B from the earlier analysis.

Applied to the dataset of J4-18-A the season of death changes slightly. Note below the command for plotting three graphs (`par`) in one line and how (a) is not part of the equation anymore but has been replaced by 0.77. Also I added a histogram of the residuals to better evaluate their distribution and check for normality. A normally distributed group of residuals indicates no inherent biases towards higher or lower values in the dataset.

```
fit=nls(y18a~0.77*sin(b*x18a+c)+d, start=list(b=0.45, c=0.3, d=-1.55))

summary(fit)
```

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
b	-0.31962	0.03336	-9.582	3.44e-11
c	6.49243	0.07440	87.266	< 2e-16
d	-0.64555	0.04116	-15.684	< 2e-16
Residual standard error: 0.1104				

Table 6.3 Results of least square analysis for the adjusted shell edge samples of J4-18-A. Note that (a) is not missing in the results as it has been predefined as a=0.77 based on modern data.

```
par(mfrow=c(1,3))
```

```
plot(x18a, y18a, ylim=c(-3,0), xlim=c(0,13), type="o", main="Sample curve", col=c("blue"), xlab="Distance from shell edge [mm]", ylab = expression(paste("δ"^18*"O"*" (‰) VPDB")))

lines(xyear,0.77*sin(-0.45*xyear+6.49)-1.55, col=c("black"))

lines(xyear,0.77*sin(-0.32*xyear+6.49)-0.65, col=c("blue"))
```

```
boxplot(summary(resid(fit)), ylim=c(-1.5,1.5), main="Range of residuals", ylab = expression(paste("δ"^18*"O"*" (‰) VPDB")))
```

```
hist(summary(resid(fit)),main="Distribution of residuals", xlab="Deviation from ideal curve",ylim=c(0,5))
```

The new model shows that the end of the sequence is not at a maximum in the sine curve but is on the slope (Table 6.3; Fig. 6.6). This is a bias that needs to be accounted for in the interpretation but it prevents short sequences to be wrongly interpreted as ending in a minimum or maximum.

As a final indicator of the fit of the sequence to the modelled seasonal curve I calculated the coefficient of determination (R^2) of the model. This was done in R using simple equations to calculate the total sum of squares (`TSS`) and the residual sum of squares (`RSS`). Their ratio is subtracted from 1 to get the R^2 value. The resulting number indicates a better fit the closer it is to 1. Models with a bad fit would result in an R^2 value closer to 0 or even a negative value. Note the additional `R2` at the end of the command to display the result of the equation.

```
TSS=sum((y18a-mean(y18a))^2)
```

```
RSS=sum(resid(fit)^2)

R2= 1-(RSS/TSS)

R2
```

For J4-18-A the R^2 values is 0.97. This is a very good value.

6.2.4 Summary

The statistical analysis is very similar to a simple visual assessment of the plotted sequential shell edge values. The aim of both methods is to find the right season for the fragment of the seasonal curve based on modern reference data. However, measuring the statistical probability of this location can provide valuable assistance for the interpretation and comparison of different sequences.

The above example were both sequences from modern shells and with known season of death. An overview of how this method evaluated the overall interpretability of the archaeological dataset from JW1727 will follow in the next section.

6.3 Statistical pre-assessment of archaeological sequences

6.3.1 Overview

The statistical analysis of shell edge sequences allowed to measure how successful the $\delta^{18}O$ values trace the seasonal change. The fit of the data (R^2) indicates how confident an interpretation of the seasonal signal of the last growth increment can be.

After testing the analysis on well studied shells from the modern environment, I now present results from archaeological shell edge sequences and on what grounds I decided to not use some shells to reconstruct seasonality. I used the R^2 value to group the sequences by quality and carried out a mixture analysis to look for obvious groups of sequences with high or low confidence in interpretation (Fig. 6.3.1).

Following the distribution of R^2-values (Fig. 6.7), there are two groups of shell edge sequences with a high (green, 0.80±0.1) and a low (red, 0.39±0.2) confidence in their interpretation. Additionally there is a distinct peak at R^2=0.95, which could be made its own group of sequences with a very high confidence. However, this is not the actual aim of this analysis. For me it is important to be able to say that there is statistical evidence that a large part of the assemblage produces usable seasonality data. Every shell in the group with a high confidence had an easily interpretable curve. This is why I decided that everything over a specific R^2 value can be analysed. This specific value is represented by the divide of both groups at R^2=0.6.

Of the 81 analysed shells, 40 shells (49%) produced sequences with R^2-values above 0.6 and are well in line with the seasonal change experienced by modern reference shells. 41 shells (51%) produced sequences with R^2-values that are less than 0.6. Some of these shells can still be interpreted but have obvious flaws and anomalies and thus their seasonal signal has a lower confidence.

The following section will give more detail on high confidence and low confidence groups and will give characteristic examples for each one.

6.3.2 Sequences with high confidence

Since the data from the modern study is being used as a reference, it was concluded that shells that follow the same trends in $\delta^{18}O$ values and growth rate (chapter 5.5), are most comparable to the modern reference data and thus their seasonal signal has the highest quality. One example for a useful seasonal sequence are the results from shell 1727-8-M-8. The sample points cover 4 mm of shell edge, which is enough to measure the overall trend of the seasonal signal and determine the season of death (Fig. 6.8).

As can be seen (Table 6.4; Fig. 6.9, left), the data points from 1727-8-M-8 describe a curve (blue line) that closely resembles the seasonal change that was found in modern shells (black line). The part of the curve at the all-year minimum, which is covered by the data points, is much higher than the modern equivalent. This is also visible at the centre of the curve expressed as (d) (d=–0.8), indicating lower temperatures recorded in the shell.

The parameter for curve-period (b) indicates a slightly slower growth rate (decrease of 6%) for 1728-8-M-8 in comparison to the growth rate from the modern study. However, this decrease is not significant and can almost be ignored.

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
b	0.51451	0.05459	9.426	8.11e-05
c	0.76611	0.13744	5.574	0.00141
d	-0.80452	0.02781	-28.925	1.13e-07
Residual standard error: 0.04704				
Interquartile range: 0.04592286				
R2-value: 0.9055453				

Table 6.4 Results of least square analysis for the shell edge values in 1727-8-M-8.

The overall fit of the constructed curve is very good. This is demonstrated by the generally small residuals (Fig. 6.9, centre), the residual standard error (0.05), the small interquartile range (0.05) and the R^2-value of 0.9. These are all indicators that the points work well together and not many anomalies exist in the dataset.

The next example will use the sequence from shell 1727-18-M-7 (Fig. 6.20) to show how an anomaly in the dataset will be evaluated by the least-square-analysis and how it changes the overall result for the seasonal signal.

The stable isotope values are similar to the values from 1727-8-M-8 but the sequence has two anomalous values in the middle and at the end of the sequence (Fig. 6.11, left). But because all other points follow a normal seasonal trend, the data points with anomalous values have no influence on the most possible seasonal curve and are instead recognised as anomalies and classified as outliers (Fig. 6.11, centre).

The anomalies do have an influence on the overall measures of fit (Table 6.5). They increase the residual standard error (0.23) and the interquartile range (0.18) as well as decrease the R^2-value (0.73). Altogether, these lower values do not make the sequence uninterpretable but they show where the problems in the sequence are and can give an estimate of their significance. Especially when anomalies are found far away from the shell edge, whose isotope values are of higher importance to the determination of season of death, their influence does cause significant problems. How I decided to address anomalies at the shell edge or very close to it is the subject of the next section.

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
b	0.66084	0.11196	5.902	7.23e-05
c	0.49322	0.31813	1.550	0.147011
d	-0.42412	0.08898	-4.766	0.000459
Residual standard error: 0.2348				
Interquartile range: 0.1811152				
R2-value: 0.7340682				

Table 6.5 Results of least square analysis for the shell edge values in 1727-18-M-7.

6.3.3 Accounting for anomalies at shell edges

A small number of sequences show a seasonal trend as it is expected based on the modern study but they also show a high degree of anomalies. This makes them more difficult to interpret. This section will use two sequences as an example for this kind of result and how it affects the interpretation of seasonality.

The sequence from shell 1727-13-M-4 consists of 10 edge samples over a 3.5 mm length measured from the shell edge (Fig. 6.12). The overall trend of the isotope values is a downward direction towards the shell edge, indicating a gradual warming of the shell environment on a seasonal scale. However, as has been found in shell 1727-18-M-7, there are anomalies in the form of values that are significantly enriched or depleted in comparison to directly neighbouring samples in 1727-13-M-4 (Fig. 6.13, left). This is especially evident in the three samples between 0.6 mm and 1.6 mm. The overall accuracy of the curve is much lower in comparison to the previous examples (Chapter 6.3.2), especially because the anomalies are close to the shell edge. The rest of the data points fit well to the curve, which is why the R^2-value is high (Table 6.6). The anomalies increased the interquartile range of residuals (0.17) as well as the residual standard error (0.20). They also decrease how well the parameters of the seasonal curve (b,c,d) fit to the calculated equation indicated by high standard errors. Each of these factors makes it more difficult to verify if the shell edge value of –1.77 ‰ is accurate.

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
b	-0.4349	0.1996	-2.179	0.0721
c	0.4834	1.0725	0.451	0.6680
d	-1.7059	0.8190	-2.083	0.0824
Residual standard error: 0.1954				
Interquartile range: 0.1736563				
R2-value: 0.7229507				

Table 6.6 Results of least square analysis for the shell edge values in 1727-13-M-4.

There are several ways of arguing for or against the accuracy of the shell edge value. The penultimate sample (–2.17 ‰ at 0.6 mm) could simply be taken out of the sequence because it clearly is an anomaly. The gradual slope of the overall sequence would become smoother. Its $\delta^{18}O$ value of –2.17 ‰ is a very low value considering the overall range of the archaeological shells. At the same time there are no obvious traces of growth recession or hiatuses in the shell growth increments (Fig. 6.12), that would indicate why there are anomalies in some samples while others plot according to plan. Without an explanation of why some values work and others do not, there is no real argument towards taking them out of the sequence apart from the fact that they do not look ideal.

I therefore decided to leave all values within the sequence and to interpret the shell edge value of –1.77 with an error equal to the interquartile range of residuals (–1.77

±0.17). This is a useful compromise when having to decide what to do with a shell sequence that is not perfectly clear. It also helps to quantify how much shell edges can or should deviate from the overall trend of the sequence. Examples of extreme deviation in shells with little confidence in their interpretation will be described in the next section.

6.3.4 Sequences with little confidence

This section presents an example of shell sequences that have anomalies similar to the ones mentioned in the previous section but in a much higher number. These anomalies are prevalent to the degree that the shell edge sequences cannot be relied on for a seasonality study.

The sequence from shell 1727-20-B-5 covers 3.8 mm with a sample number of 10 (Fig. 6.14). Different from sequences with a high confidence in their interpretation (Chapter 6.3.2), the sequence of 1727-20-B-5 is so irregular, that almost no data points would fit well together (Table 6.7; Fig. 6.15, left). The overall trend of the sequence is indecipherable, which is mirrored by the accuracy of the curve parameters, the residual standard error (0.2664), the R^2-value (0.14) and the range of residuals (IQR= 0.23, Fig. 6.15, centre). While the constructed curve looks similar to the reference curve in terms of growth rate (b=0.48), there is no real reason to assume that this curve is real as is shown by the large standard errors of each parameter that would also allow less similar curves. Equally, the position of the data points at the constructed curve minimum is not certain but merely the most probable solution that was found by the least-square-analysis.

The reason for the bad quality of the sequence is unknown. Even though the shell broke during the sample preparation, it did not get destroyed beyond recognition. It is possible that the irregular growth patterns in the shell lip are results of storm or spawning events, whose effects on the mollusc are still unknown. It is probable that the conclusions that were made in the modern study (Chapter. 5.5) are not fully applicable to other shell edges or other parts of shell edges. This especially includes very old shells that have had a distinctive lip at their aperture for a long period.

Formula: y ~ a * sin(b * x + c) + d				
Parameters:	Estimate	Std. Error	t value	Pr(>|t|)
b	0.4817	0.2487	1.937	0.09390
c	0.5813	0.5766	1.008	0.34691
d	-0.5986	0.1223	-4.896	0.00176
Residual standard error: 0.2664				
Interquartile range: 0.1693815				
R2-value: 0.1394757				

Table 6.7 Results of least square analysis for the shell edge values in 1727-20-B-5.

In terms of interpretability, this category of shells is the least meaningful. Apart from other shells, similar to 1727-20-B-5, it also includes a number of shells (n=6) that had such a bad quality, that no reasonable seasonal curve could be constructed. Statistical values for them, their curve parameters or their residuals do therefore not exist. The category as a whole will not be part of the seasonality study.

6.3.4 Summary

The quality of shell edge sequences from JW1727 was successfully assessed by the statistical analysis of their ability to conform to the seasonal change recorded in the modern study. It was possible to categorise the sequences into two distinct categories based on their individual statistical values.

It was also possible to find a way to address irregularities within the sequence by applying an error to the terminal shell edge value that is equal to the interquartile range. Every shell edge sequence was processed using the least-squares analysis for nonlinear functions in R. A plot of the $\delta^{18}O$ data with the most likely seasonal curve created by R is displayed in Appendix 4 together with the isotope data and the statistical values.

Considering these results, the seasonality study of shells in JW1727 can have a more objective view as it is now possible to exclude shells from the seasonality study that statistically do not correlate with the seasonal change that can be expected to be recorded in the shell.

6.4 Growth variations and changes in $\delta^{18}O$ in archaeological specimens

After having assessed that the seasonality data produced from by shells from JW1727 can be interpreted with confidence despite there being a lack of knowledge regarding the shell ecology, I will now try to explore the impacts of growth variations on the $\delta^{18}O$ composition in the shell edge sequence. More specifically, this section will analyse the growth variations in archaeological shells and see how they correspond with the $\delta^{18}O$ values of the analysed increments. I also explore the possible indicators in the shell structure that would definitely produce anomalies in the stable isotope sequence. This way, future seasonality studies can target certain shells for stable isotope analysis, that have a higher chance of producing consistently high quality shell edge sequences.

This section will begin with an examination of shell growth increments with obvious growth hiatuses and how these influence the isotopic record. This will be followed by a closer look at shells with clear growth structures and their typical shell sequences. The section will conclude with guidelines on which shells should be targeted for future seasonality studies and which shells should be avoided.

The most of the analysed shell sections that were part of the seasonality study show signs of obvious growth interruption. These are usually accompanied by smaller growth increments and a higher organic content in the growth lines. As mentioned before (Chapter 4.2.) the amount of organic material in the increments increases because specific events (tides, storm events, extreme temperatures) have an effect on the mollusc's metabolism and can cause it to change into an anaerobic state. During this time the amount of acidic components increases, which the mollusc tries to buffer with the calcium carbonate from the shell edge. This means that the growing shell is being chemically eroded at the same time, which results in a slower growth rate. Parallel to this, the organic content is still being caught in the shell at the same rate, which results in a higher concentrated organic content of the increment.

A good example of this is shell 1727-13-M-3 (Fig. 6.16). Here two distinct growth interruptions in the form of darker growth lines can be found on the shell lip. They are accompanied by deep V-shaped notches that might be the result of a sudden change in temperature (Kennish 1980). These changes can occur seasonally but can also be the cause of any rapid changes in the environment like storm events or extreme tides. Equally important as changes in the environment are changes that are linked to the physiology of the mollusc. Spawning events or other causes of stress can have a strong impact on the shell growth.

Comparing the growth structure of 1727-13-M-3 with the growth analysis in the study of modern specimens (Chapter 5.5), it is obvious that 1727-13-M-3 is probably older, as it has a longer adult lip part than the analysed modern specimen (Fig. 5.17). Resulting from the length, it was estimated that the time that was recorded in 1727-13-M-3 was about 6 months, which is three times what was recorded in the modern growth analysis (2 months, Fig. 5.18). When adding the $\delta^{18}O$ data from the corresponding shell sequence, it is obvious that this is far from the truth (Fig. 6.17+18).

The sequence covered about 5 mm of growth increments but has $\delta^{18}O$ values from two summers and two autumns, exceeding the estimated time of about half a year (Fig.6.17 and 6.18). A continuous growth pattern can be excluded. A main gap between $\delta^{18}O$ values of samples 5 and 6 (–1.44 ‰ and –0.52 ‰, respectively) is also obvious in the sequence at 2 mm distance from the shell edge. This gap corresponds well with a distinct, dark growth increment at a distance of also 2 mm from the shell edge (Fig. 6.17). It is possible that this growth increment with a high amount of organic material and a deep V-shaped notch is the result of an event that caused the shell to stop growing. At some point in winter it stopped and only continued after several months when temperatures were much higher resulting in a distinct drop of $\delta^{18}O$ over a short distance in the stable isotope sequence (Fig. 6.18).

Confusingly, this connection cannot be assumed for all growth increments. There is another distinctly dark growth increment at 1 mm distance from the shell edge, which lacks the change in isotope values even though it has the same appearance and the same distinct notch at the shell exterior. One would expect the $\delta^{18}O$ values of samples 2 and 3 (–1.19 ‰ and –1.27 ‰, respectively) to be equally distinct as samples 5 and 6. Under what circumstances the distinct growth line was created is not obvious. Evidently this cannot be solved by comparing it to the stable isotope values.

When comparing 1727-13-M-3 with two shells from the same archaeological context (1727-13-M-6 and 1727-13-M-7), the meaning of distinct growth lines for the following stable isotope sequences becomes even more enigmatic (Fig. 6.19-22). 1727-13-M-6 and 1727-13-M-7 are of a similar size and were sampled at the same resolution. They also both show distinct growth lines close to the shell edge, which might be a result of the same events. Accordingly, their isotope sequences should be very similar. This is why they have been sampled in a similar way. Both sequences have one sample point before the distinct, dark growth increments, followed by one sample point overlapping the dark growth lines and then continued by all the subsequent sample points in the growth increments preceding the dark ones. Despite the similarities, both sequences seem to not only cover different time spans, but also end in different seasons and do not show any signs that the darker increments cause greater gaps in the isotope record than normal growth increments.

This problem is unlikely to be solved until there has been found an adequate method to analyse the growth patterns of shell increments in *C. fasciatus*. The lack of knowledge of what is happening in the increments before and after growth interruptions is the missing link. Since the use of thin-sections and the use of Mutvei's solution has not been successful this information will remain unavailable until further studies.

Even though there are clear and easily interpretable stable isotope sequences from shells that have dark growth increments, it is worth looking at shells that lack these distinct growth patterns. Shell 1727-8-M-8 shows a regular growth, with no clear signs of events that have caused a physiological reaction by the mollusc (Fig. 6.23). Similarly, there are no anomalies within the shell and it almost perfectly describes the seasonal temperature change that one would expect (6.24). It also has a fairly similar growth rate to the 13 mm/year rate that was established based on the modern growth increments. This has likely to do with their similar size and shape.

A lack of visible growth variations is a very common characteristic in shells with isotopic sequences of high quality. Whether this is because they are from a more stable environment or are healthier specimens is not clear. However, it is apparent that the older a shell gets, the more likely it is to slow down its growth and to be more vulnerable to environmental impacts and physiological hardship that cause growth cessations.

Interestingly, when looking back at shells from layer 13 it becomes apparent that none of them has darker growth lines at the beginning of the adult lip part of the shell. A time equivalent to the beginning of adulthood. There is a clear area of several millimetres of growth increments that are very similar to 1727-8-M-8 and other shells of equal age and homogeneity. It might be possible that at this age *C. fasciatus* shells are less likely to exterior factors that cause growth variations.

In summary, there are two conclusions that can be drawn from the comparison of stable isotope values and a very basic assessment of growth variations. First, there is no obvious relation between the creation of growth increments with high organic content and anomalies in the $\delta^{18}O$ sequence. Similar increment structures produced completely different shell edge sequences.

Second, the lack of growth increments can be indicative of an absence of anomalies in the isotope record. It is worth noting that there seems to be a lack of growth variations in parts of the shell that are equivalent to young adults. Consequently, future studies should explore the possibility of using shells for stable isotope analysis that are predominantly this age and assess if they might be a better source for seasonality signals.

6.5 Summary

Building on the modern study (Chapter 5) this chapter aimed to assess the possibility of using *C. fasciatus* specimens as a reliable proxy to assess the season of death. The use of statistical analysis as an estimate for robustness of shell edge sequences made the interpretation of the seasonality data more objective.

My own method of assessing the growth rate and season of death using the statistical program R is made to objectively include or exclude sequences based on the overall robustness of the data.

The method takes into account the overall seasonal trend of the data, it can differentiate between outliers and seasonal trends and can statistically sort out unclear seasonal signals.

The inconsistency in what growth increments mean for the sequential sampling of shell carbonate for stable isotope analysis, is a problem that needs further analysis, but the statistical values for these unclear sequences helped to measure the overall impact on the seasonality study and to quantify how interpretable they are. This way it allows the most efficient use of the available resources to achieve the maximum number of sampled shells.

I showed that the interpretability of shell edge sequences is not directly related to the amount of shell edge samples but to the robustness of the curves. The limits that are set by time and funding should not result in overly long sequences but in sequences that are clear and high in number.

With this chapter I hope to have made the foundation of a comprehensive and objective seasonality study, that uses a shell species, which is hardly analysed. In the following chapter I will present the results of the seasonality study and present the data from the shells in their archaeological context.

Chapter Seven

Archaeological Study

7.1 Introduction

After the theoretical framework for shell middens in general and the environmental framework of the Farasan Islands in particular have been considered, I now present the seasonality study of the shell mound JW1727. This chapter is the core of this study. It presents the seasonal signals from shells hand-collected during the excavations in 2013, after they were sampled with the methods developed in chapter 5 and their stable oxygen isotope sequences were evaluated using the statistical method developed in chapter 6. The resulting seasonal signals are here combined with stratigraphic information in a rapidly accumulated shell mound to assess how rapidly parts of this mound accumulated and how often shellfish were harvested. Through this I hope to draw general conclusions about the shellfish exploitation that are applicable to the majority of shell mounds on Farasan.

The first section of this chapter gives an overview of the shell mound (**Chapter 7.2**) and the sampled layers (**Chapter 7.3**). Then the seasonality data of each layer are given with a thorough description of the dataset (**Chapter 7.4**). The chapter concludes with the possible implications for the whole of JW1727 (**Chapter 7.5**). The implications for the island and the Red Sea coastline in general will follow in chapter 8.

7.2 Archaeological context of JW1727

Shell midden JW1727 is located in the Northwestern part of Janaba Bay and today is at a 0.75 km distance to the sea due to local sea level change in connection to uplift (Fig. 7.2.1). The shell mound has a dominant position in the landscape as it sits on a distinct palaeo-shoreline. It is located on a sand ridge along a palaeo-coastline and in line with several dozens of similar shell middens. It is about 2 m in height and 30 m across. Because of its large size it was a good chance to access a long stratigraphy of shell deposition. Interestingly, despite its size the radiocarbon dates indicated a very short accumulation period of under two decades. Samples from layers 2, 17 and 23 all dated to around 4,800 cal.B.P. (Table 7.1, Fig 7.3). An estimation of the accumulation interval showed a probable accumulation period between 16 years (68.2% probability) and 82 years (95.4% probability). This is a very fortunate characteristic as a rapidly accumulated shell mound is more likely to have preserved distinct episodes of deposition that have accumulated on a seasonal scale and whose accumulation rates can be measured by seasonal proxies.

Lab no.	Layer	^{14}C-Age	Mar. Res. Corr.	BP Range 2σ	Material	Species
OxA 28,009	2	4851 ±31	-100 ±50	5108-4873	shell	Mussel (*Brachidontes* sp.)
OxA 27,890	17	4202 ±29		4835-4660	charcoal	unidentified
OxA 27,889	23	4287 ±29		4861-4838	charcoal	unidentified
OxA 28,617	23	4701 ±28	-100 ±50	4907-4735	shell	Mussel (*Brachidontes* sp.)
OxA-31169	27 - basal	5044 ±35	-100 ±50	5444-5064	shell	Mussel (*Brachidontes* sp.)

Table 7.1, Radiocarbon dates for JW1727. Note that the basal sample from the bottom of the trench dates a layer of crushed shells that are part of a beach deposit. Marine reservoir correction is based on paired charcoal and marine shell samples (Williams 2011)

In February 2013, the DISPERSE team excavated a 1 m wide and 10 m long trench from the rim of the mound towards the very centre (Meredith-Williams et al. 2013). This was done on the premise that the mound was built symmetrical and shells mostly deposited on the top of it. This would put the beginning of the mound in its centre and at the inside wall of the trench. The actual beginning of the mound remains open to speculation as the excavation did not expose the whole site. However, the stratigraphic sequence indicated a fairly straightforward pattern of deposition, where if not the initial, at least a very early part of the midden, has been recorded (Fig. 7.4). If that is the case, then the exposed section captured the whole extent of the depositional history of the mound from the very beginning to the very end of its occupation. The east section of the mound has not been recorded in detail as it seemed to be similar to the opposite profile in the 1 m trench. However, subsequent photogrammetry of the trench revealed a cut in the eastern part of the shell midden (Fig.7.5) that is very similar to a cut discovered in 2009, which was related to a burial in JE0004. Due to limited excavation time the trench has not yet been extended to clarify the origin of the cut.

Generally, JW1727 shows a clear dominance of *C. fasciatus* shells in combination with a variety of other gastropods, mostly *Ostrea* sp. and *Arca avellana* (Fig. 7.6). There could be a change in exploitation in the higher layers where more mixed layers dominate, however if this was related to environmental change like it was proposed for JE0004 is questionable given the rapid accumulation time of 16 to 82 years.

Given its location, this shell mound is clearly associated with other shell mounds of similar size on the same palaeo-shoreline. However, whether they are similar in terms of exploitation patterns is not yet understood. However, compared to earlier

(JW1705) and later sites (JW5694, 5719, 5697) it is likely that there is some change due to the shift of the shoreline (Chapter 2.7).

A column of bulk samples was taken from the exposed section at the inside wall of the trench. The samples were taken by stratigraphic layers and in 10 cm spits where possible. The bulk samples measured 25 x 25 cm in area and were ~6 litres each. The detailed analysis of the samples was carried out by Eva Laurie. Only sieving and preliminary sorting into shell remains and sedimentary matrix (when available) was carried out in the field to reduce the sample weight before transport.

The main constituent of JW1727 is *C. fasciatus,* although several mixed layers also show varying amount of mussels (*Mytilus* sp.) and other bivalves (Fig. 7.7). The bottom layer of the mound is the palaeo-surface of the sand dune that the shell mound is located on. Here it was possible to locate several different events of sediment accumulation including layers of naturally accumulated shells.

On top of these natural layers was a layer of mixed shell with a high concentration of *C. fasciatus* (layer 23), which is believed to be the (or one of the) initial depositions that started the construction of the mound. In the centre part of the mound was a cut into the initial layer and into the sand dune that had subsequently been filled with *Chicoreus* sp., which could be interpreted as a posthole. Similar cuts were found that had been filled with *Chicoreus* sp. specimen higher up in the stratigraphy and on other sites such as JE0004 and JW1807 (Meredith-Williams et al. 2013). These could have been used for positioning posts or stakes into the less stable layers of small gastropods to steady dwelling structures that are put on top of the mound. Since no remains of such structures were found, any interpretation of these features is only tentative and will not be made here.

Very characteristic for the JW1727 shell mound is the thick layering of *C. fasciatus* shells with occasional layers of charcoal and fishbone, and bivalves (15,17) as can be seen in layers (20), (18), and (16), that are divided by lenses of charcoal and mixed bivalves. For those layers the drawing of the stratigraphy is flawed in some respect. There is no obvious way to divide the thick *C. fasciatus* layers into distinct stratigraphic units (e.g. 16a, b, c) in parts where distinct charcoal (or other) lenses do not occur. They might not have existed or they have been disturbed and integrated into the surrounding shell. This is especially the case at the outer margin of the mound.

A change in preservation or processing techniques is possible for *C. fasciatus* strata higher in the section profile. An undisturbed *C. fasciatus* layer shows distinct changes in colour from one stratum to another, changing from intense orange (14b), to green (30), back to orange (14a), and to pure white (13), without changing density, matrix or any other typical layer characteristic. Above this package of *C. fasciatus* is an extensive layer of ash mixed with *C. fasciatus*. This follow layers of similar nature as below; thick *C. fasciatus* (10, 8, 5) divided by thin bivalve layers (9, 6).

On the very top of the mound we find mixed layers with the occasional ash pocket (1,2,3,4). Most changes in layer composition were distinct in the section profile but became less distinct in the analysis of the bulk samples, because here *C. fasciatus* is the dominant species in all layers. This can be the result of how the layers were perceived during the excavation as having relatively more bivalves as other layers.

In the southern part of the trench the layers become less distinct and larger. They are also likely to be disturbed and partially re-deposited on the slope of the mound. The disturbance is traceable by the disappearance of thin layers, which are mixed into the overlying and underlying layers, and the overall dominance of mixed layers at the bottom of the slope. Most layers are cut off at the top and end in a disturbed layer of mixed composition and higher amount of matrix that contrasts the overall clast-supported nature of the mound.

7.3 Description of sampled layers and sampling strategy

Overall, six layers (1, 8, 13, 18, 20, 22) were chosen for the seasonality study. As described in chapter 3.6, this study does not only aim to gather seasonality data for the purpose of finding out if the site JW1727 was occupied seasonally or during the whole year, it also aims to compare the seasonal signal from the beginning to the end of distinct layers, to understand the length of single episodes of accumulation.

I argued that this is a suitable measurement of the exploitation patterns that generally took place on the Farasan islands. This is why, apart from some small layers throughout the midden, three thicker layers of *C. fasciatus* (8, 13, 18) were chosen from the end section of the trench in JW1727. The shells were picked out of the exposed and cleaned section after the drawing of the section profile and packed into bags according to their layers and sublayers (Table 7.2). All sampled layers predominantly consisted of *C. fasciatus* (layer 1: 75%; layer 8: 98%; layer 13: 83%; layer 18: 93%; layer 20: 73%; layer 22: 94%).

Layer	MNI in layer	Sublayers	Hand collected	Sampled	Successful interpretation	% success
1	177	T	16	2	1	50%
		B	7	5	2	40%
5	162	A	22	1	1	100%
8	317	T	9	5	5	100%
		M	16	8	5	63%
		B	7	6	4	67%
13	73	T	3			
		M	13	7	7	100%
		B	7	7	3	43%
18	484	T	9	3	3	100%
		M	13	8	7	88%
		B	10	7	7	100%
20	220	T	7	7	5	71%
		B	8	8	4	80%
22	263	A	28	7	6	100%
Total	1696	15	175	81	61	**Average 79%**

Table 7.2, Numbers of collected, sampled and successfully analysed C. fasciatus shells per layer. Also the MNI from bulk samples of the layers is reported. Note that the stratigraphic information of the bulk samples has a lower resolution than the hand picked shells. Abbreviations T, M and B stand for "top", "middle and "base", respectively.

Layer 8 is a distinct layer of pristine *C. fasciatus* shells with a thickness of between 11 and 8 cm. It is slightly sloped downwards towards the rim of the mound. It overlies a layer of bivalves (9) and is covered by a dense layer of charcoal (7). Both borders are distinct and no mixing seems to have occurred. 32 shells have been collected, from which 19 were sampled for stable isotope analysis. The shells are grouped into "top" (n=5), "middle" (n=8), and "base"(n=6) depending on their location within layer 8. I tried to collect as many completely intact shells as possible. In some cases only the lip section of the shell was retrieved. This was because the sample location of the shell was more important for analysis than its degree of fragmentation. The borders of the sublayers were important but also how far apart the shells were horizontally. They were more likely to be part of the same episode of deposition the closer they were together.

In layer 13 a similar sampling strategy was carried out. However, only 23 shells were collected because a higher degree of fragmentation in the top part of the layer left less shell edges in a condition that was suitable for analysis. While the middle and the base layer had both 7 shells, the top layer only produced 3. Layer 13 is slightly larger than layer 8 with a thickness of 10–15 cm, but has an identical slope towards the peak of the mound. Additionally, the composition is very similar, it consists of mostly *C. fasciatus* and has little to no sedimentary matrix. It is covered by a *C. fasciatus* layer mixed with ash (12) and overlies another *C. fasciatus* layer with a distinct orange staining of unknown origin (14). Layer 13 can be traced over 4 metres along the perpendicular section of the trench and is finally cut by a mixed layer of *C. fasciatus* and bivalves.

The last layer that I focused on during the analysis was layer 18. It is also a *C. fasciatus* layer with little to no sedimentary matrix and pristine preservation of shells, both indicators of rapid accumulation processes and quick covering by other shells. However, it is much bigger than layers 8 and 13 with a thickness of 25 cm, and shows distinct lenses of charcoal and bivalves. These lenses were not found in layers 8 or 13 and suggest that despite the first impression, layer 18 might not be one single episode layer but actually several *C. fasciatus* layers that can only be distinctly separated in locations with shell accumulations of different composition. Shells have again been chosen for analysis from the top (n=3), the middle (n=8) and the bottom (n=7), however due to the obviously discontinuous deposition of shells, they are expected to show a much bigger variation in their season of death than shells from layers representing shorter episodes of accumulation (i.e. 8, 13).

Additionally to the three bigger layers, some smaller layers were analysed. However, no division into sublayers was carried out as they were simply too thin or obviously disturbed (1, 22).

The shells were analysed according to the methods described in chapter 5. Almost all shells were adult and were solely sampled on their lip parts.

7.4 Results of seasonality analysis

7.4.1 Overview

This section presents the results of the seasonality assessment. It gives a broad overview of the results as a whole and then describes the results of shell sequences by single layers.

As mentioned in the previous chapter, a number of shell edge sequences were not able to provide $\delta^{18}O$ values that could be interpreted with confidence. This was assessed by the use of the calculated R^2 value as well as the correlation between the terminal edge value and the trend of the curve as a whole. Overall, 40 (49%) shells produced R^2 values above 0.6 and were able to be analysed with with confidence. Of the 41 (51%) shells who had lower R^2 values 21 (26%) still produced comprehensible edge sequences. This leaves 20 (25%) shells with unsolved seasonal signals. However, to examine if there are any seasonal biases from shells with a high confidence or a low confidence in their interpretation, I also included the lower 25% in the distribution of seasons.

The result showed a similar distribution of harvested shells throughout the year with no clear dominance of any season. This means that non-interpretable sequences do not give a false indication for a preferred season, which would mean a bias for the dataset, but for all of them equally. Regardless of this, shells with low interpretability are not part of the following results but are presented in Appendix 4. The remaining sequences of $\delta^{18}O$ values from JW1727 showed a variety of seasons of exploitation (Fig. 7.8) with a preference for the second half of the year.

The largest number of shells are likely to have been collected in the second half of the year with summer-autumn (n=16, 26%) and autumn (n=16; 26%) representing over half of the exploited shells, while most of the other seasons range between 5 and 8 harvested shells. Only winter and winter-spring have a lower presence of harvested shells.

7.4.2 Layer 1

From the 7 shells that were analysed from layer 1, only 3 produced good quality isotopic sequences (1727-1-T-2, 1727-1-B-5, 1727-1-B-6). Surprisingly, every shell that was sampled more extensively with 20 measurements resulted in sequences that showed little variation (1727-1-B-1) or variation that could not be explained only by temperature change (1727-1-T-1).

Whether this is the result of the sampling sequence covering both juvenile and adult parts of the lip, or an underlying factor that has not been considered, is unknown. While the shell from the top had a summer-autumn signal, both interpretable shells from the base indicated winter-spring and spring exploitation (Fig. 7.9).

7.4.3 Layer 8

The sample sequences of shells in layer 8 were mostly successful. Of 19 sequences 5 failed to produce seasonality data. The uninterpreted shells either fell into the category of non-interpretable sequences or were unsuccessful in the production of $\delta^{18}O$ values in the mass spectrometer.

In general, the seasons of exploitation in layer 8 are between spring-summer and winter (Fig. 7.10). The top part of layer 8 is characterised by shell edge sequences that all follow an upwards trend from typical summer values at –1.5‰ to around –0.9‰, indicating a gradual cooling of the sea surface water. The middle part of layer 8 contains shells from the summer with edge values ranging between –1.25‰ and –1.75‰. This trend is followed by shells from the base of the layer that have similar edge values between –1.29 and –2.03, with the latter being from shell 1727-8-B-4 that has a sequence with an interquartile range of residuals of ±0.23, which could explain the fairly low value. There is a divide between the beginning and the end of the layer, which can be described by looking at the distribution in the individual sublayers (Fig. 7.11). Plotting the sequences onto the seasonal curve of modern estimated $\delta^{18}O$ values, it is apparent that they follow each other in relation to their isotopic signals and cover a time period of about 7 months. The correlation of stratigraphic and isotopic information is striking and its implications are examined further below (Chapter 7.4)

7.4.4 Layer 13

Sample sequences of shells in layer 13 show a wider range of harvesting seasons but also a peak in autumn and autumn-winter (Fig. 7.12). Of 14 sequences, 4 failed to show convincing results as there was almost no isotopic change occuring that could be linked to seasonal change. This was especially a phenomenon seen in shells from the base of layer 13 (1727-13-B-1,4,5,6). All of these sequences had some isotopic changes, but none of them were gradual or followed a certain trend, which is why they are not incorporated into the interpretation of seasonality. The shells from the basal part of layer 13 indicate a wide range of seasons of exploitation, which is mirrored by shells from the middle part also included winter and spring.

7.4.5 Layer 18

Layer 18 was the most successful layer in terms of clear seasonal signals. All but one sampled shell could be analysed (1727-18-M-3). Because of the high variation of the isotope values it was not possible to definitely assign it a specific season of harvest, even though the shell edge value itself shows a summer signal. The seasonal signals from successful shells fall into almost every season with a peak in summer-autumn (Fig. 7.13).

7.4.6 Layer 20

Interpretability of shell edge sequences in layer 20 was below average with more than 40% of sequences being either questionable or completely insufficient for the determination of seasons of death. The remaining shells are distributed similarly as layers 8 and 13 in the second half of the year with 2 additional shells falling into spring (Fig. 7.14).

The seasons indicated by shells from the top of the layer are restricted to late summer and autumn, while shells from the base of the layer plot in the seasons from late summer to late autumn and additionally in spring.

7.4.7 Layer 22

Layer 22 is the initial layer of preserved deposition at JW1727. The seasons of harvest are distributed with relatively many shells deposited in the first half of the year (Fig. 7.15) and only some from the early autumn. Why there seems to be a different distribution of seasons is not clear, however it could be a sampling bias as the number of shells is only 6.

7.4.8 Summary

Looking at the overall distribution of seasons throughout the layers shows a variety of exploitation habits (Fig. 7.16). While some layers are restricted to the cooler parts of the year (1, 8, 13), others cover a whole range of seasons (20,22).

In most layers the problematic quality of shell sequences had a large impact on the seasonality study. Even though the shells with questionable interpretability were distributed evenly throughout the dataset (Fig. 7.8), they would have an impact on the interpretation in some cases (layer 1). It is possible that the resulting small seasonal range is caused by a small number of samples. However, small seasonal ranges are also found in layers with a large number of samples (8) and equally, layers with small sample numbers were found to have large seasonal ranges (22). Still, the complications of a small sample size are noteworthy.

7.5 Discussion of seasonality data

The results of the seasonality study show three main patterns, (I) a general distribution throughout the year, indicating that there were no major reasons that kept people from collecting shells in certain seasons, (II) a general emphasis on summer and autumn harvesting throughout the midden, (III) an intense exploitation over a period of several months resulting in a shell deposit that contains layers with sequential seasonal signals, rather than a layer with a mix of multiple disconnected seasons or only one season. In the following section I address and explore each of these three patterns

I. **The ability to exploit shellfish throughout the year is linked to several preconditions, primarily seasonal availability of food sources and the mobility of the human population.** The fact that there is evidence for occupation periods in all the times of the year, makes it possible to rule out some presumptions of subsistence on Farasan. Fitzhugh (1995) described that fishing communities of Kodiak Island (Alaska) made a conscious effort to refrain from collecting shellfish during the summer to avoid being poisoned by toxic blooms. Also Meehan (1982), mentioned the seasonal unavailability of shellfish because their exploitation was connected to the seasonally changing estuarine environment. Evidently, the results above show that *C. fasciatus* was available throughout the year; no general seasonal impact on the environment has caused the mollusc to migrate to a different or inaccessible location or to be otherwise unavailable or unfavoured. In fact, shells were collected in all seasons, and this is true both for all layers taken as a whole and for individual layers, except where the sample size is too small. Otherwise, there would be gaps in the seasonal distribution found in all layers.

As described earlier, Eerkens et al. (2013) found complementary seasonal distributions in two shell mound sites at the Californian coast and argued that some of their occupants were seasonally moving from one site to the other. The supposed base camp experienced a seasonal decline and simultaneously the ephemeral camp shows evidence of exploitation in that same season. In contrast when the exploitation intensity increases at the base camp, the exploitation at the ephemeral camp completely ceases.

Evidently, there were people using JW1727 at every time of the year; so no general seasonal migration can have occurred. Note that this does not mean that shells were exploited and deposited constantly throughout the year. Gaps are indisputable but they are not linked to specific seasons.

II. **A general emphasis on summer and autumn collection throughout the midden.** Seasonal changes in the diet can be caused by seasonal changes of population size due to migration (Eerkens et al. 2013). However, the use of other food sources needs to be considered in context with coastal exploitation (Marín-Arroyo 2013). Seasonally available or more dominant food sources than shellfish or *C. fasciatus* in particular have been discussed in other studies. For coastal sites in Europe with higher latitudes the impact of winter on the terrestrial life and on terrestrial food sources has being discussed (Hufthammer et al. 2010). It has been argued that in winter there are more readily available food sources to be found at the coast, because of the lack of vegetation and animals migrating into warmer areas. It is likely that the Farasan Islands being at a much lower latitude than northern European sites have an opposite situation, where because of the high temperatures and aridity there is less vegetation in summer and more vegetation in winter. This would shift the seasonal bias of coastal exploitation towards summer because that is when there are less terrestrial food sources available. In comparison, the Mediterranean site of Franchthi Cave, Greece (Deith 1988), showed a similar seasonal increase of shellfish exploitation at drier times of the year. The site itself is located in the Peloponnese where precipitation is relatively low at under 12 mm from June to August and average daily temperatures from June to September are above 23ºC (Hellenic National Meteorological Service - HNMS 2015). This dry season comes to an end in October, when wild plants (*horta)* become available and stay available until spring. In these seasons the number of shellfish was relatively small (autumn: n=4, winter: n=7). In contrast, the highest peaks in shellfish exploitation can be found in spring (n=11) and summer (n=20). Additionally, Deith (1988) argues that the greater attraction of shellfishing in warm water could have increased the amounts of gathered shellfish in the summer. In contrast, the ethnoarchaeological and archaeological record from fishing communities in higher latitudes showed no restraint when it comes to fishing in cold temperatures (Yesner et al. 2003). How much of this is a factor on Farasan is debatable as the water temperature does not go below 25ºC. Despite this, personal communications with local fishers and rangers from the wildlife commission on Farasan showed a definite reluctance to go diving in winter as it was perceived as too cold. Whether the mid-Holocene population shared this perception is open to discussion.

III. **An exceptional accumulation rate in the dataset, where exploitation is so frequent and so intensive that shell deposition and seasonal temperature change are equally fast so that the gradual temperature change can be tracked by putting the analysed shells in their stratigraphic order.** The occurrence of intense exploitation over several months is in itself not a surprise as it is implied by the increased exploitation in summer and autumn (Fig. 7.4.2). However, the preservation of this sequential deposition in one location is remarkable. From the base to the top of layer 8 (10 cm thickness, 3-4 cm spits) a gradual change in $\delta^{18}O$ values from -1.5‰ to -0.5‰ took place, covering the isotopic change from early summer to late autumn and indicating a continuous deposition period within one layer.

A similar situation was found in the Culverwell midden (Mannino and Thomas 2001), where a decrease in shell size throughout sequential spits of the layer 8 indicates intense and continuous exploitation (not to be confused with the layer 8 of this study). This was accompanied by little change in seasonal signals based on the $\delta^{18}O$ values of terminal growth increments from the marine gastropod *Phorcus (Osilinus) lineatus* (Mannino et al. 2003). The shell edge $\delta^{18}O$ values from shells within layer 8 ranged from 1.2‰ to 2.5‰ and indicated an autumn to winter exploitation period. Regardless of the shell sizes, shell edge $\delta^{18}O$ values from only two seasons that could be connected were also found in two other layers (9+12) of the Culverwell midden. This could indicate some sort of stability and sustainability of exploitation patterns.

However, the lack of more detailed stratigraphic information about where in each layer the shells originated prevents me from comparing the stratigraphic and isotopic particulars of each shell. Combining them could improve the understanding of how the layer accumulated and rule out scenarios where shells were actually deposited in multiple autumns and winters that now form layer 8. Indeed, the decreased shell sizes in the lower spits of layer 8 indicate some degree of undisturbed succession in relation to the proposed overexploitation, but this is far from being a substitute for detailed stratigraphic information. While, the decrease in shell size might well indicate a continuous succession, it does not provide detail about the time span of succession, which is here only given by the range of shell edge $\delta^{18}O$ values.

Figure 7.17 shows the gradual change of the $\delta^{18}O$ values from shell edges and clearly shows some degree of overlap between neighbouring spits. The overlap and the fairly stable isotopic signal during summer makes it difficult to fully ascertain the occupation time. Using the beginning and the end of summer as earliest and latest possible start of occupation, different time periods can be found (min: 3 months, max: 9 months). However, including the overall sequence (Fig. 7.11) and the statistically predicted growth rates of the shell sequences (Appendix 4), it is possible to further specify the beginning of the occupation time and set it to early summer, which translates into an overall period of ~7 months.

Interestingly, no other sampled layer showed this succession. Almost every other layer showed seasons from every part of the year when the number of sampled shells allowed it. This could imply a change in exploitation patterns and a rapid accumulation event in only layer 8, possibly a special scenario where much more shellfish was eaten than usual. It could also be possible that during this time JW1727 was simply frequented more often than it was in other times, which would result in a more frequent shell accumulation. Whether this is connected to an increase in population size or the decline in the availability of other food sources is unknown. It is similarly difficult to ascertain if people processed shellfish at JW1727 more often during layer 8 because they lived closer to it. Collecting and processing the shells closer to home seems favourable (Kim 2010) and it would result in more shells accumulating in less time. However, since we neither know about availability of food sources nor about where people stayed, these reasons cannot be used to explain a different accumulation rate in layer 8.

It could be argued that the shells outside layer 8 accumulated with a similar rate but were deposited in an already disturbed state. The shells could have been processed somewhere else (location A), temporarily deposited at location A and after location A was cleaned, the shells were deposited in bulk creating layers 13, 18, 20 (location B). Following this the gradually accumulated shells, even though having once been in sequence, can now only be found as a disturbed layers or as a layers that hide the shells' shared history. They would then appear to produce a seasonal signal for the layer that a) seems to cover seasons from different years, b) are disconnected accumulation episodes and c) are subsequently erroneously interpreted as a slowly accumulated shell deposit. This scenario would entail a lot of work and it is not clear, why this work would be necessary or useful, because the place that the shells are in now already seems to be a useful place to put them just after collection. This is why I rule out secondary deposition.

Another possibility is that the other layers have been disturbed after shell deposition. i.e. the shells from a single summer to winter episode were subsequently mixed by human or animal activity with shells collected at other times and other years. In contemporary times this is already happening in the top layers of some middens on Farasan, because they are used to sit and dine on, as well as to drive over with cars and motorbikes. To what degree similar processes would have happened during prehistoric times is unknown, but the lack of sedimentary matrix in most layers would definitely allow for subsequent mixing of the loose shells from different seasons to happen. At the same time however, the stratigraphic layering of JW1727 is distinct and none of the layers in the column look like they are mixed. The seasonal change found in layer 8 is found in 3 spits over 10 cm. Layer 18 is larger than this but layers 13 and 20 are of similar size. Any mixing between invisible seasonal spits without the mixing of layer boundaries is unlikely to happen on this scale.

If the secondary deposition of mixed layers is unlikely, as well as the mixing of individual layers without mixing layer boundaries, is it still likely that the accumulation rate of the other layers is similar to layer 8 and the stratigraphic disorder of shell seasons misleading? The simplest explanation is that although the excavated section implies that the centre of the mound was found, and that it was possible to sample each accumulated layer from the beginning to the end, I have in fact sampled most layers in locations that are not actually the "top" or the "base" of the layer. The layers accumulated in three dimensions not in two, as suggested by the section drawing. It is very possible that in many cases the section exposed not the centre of the shell deposit but its rim. By sampling shells from the "base" of the layer, I could have actually sampled rims of different seasons because the excavated section cut the layers at different places. In this context it is possible, that the accumulation rate of layer 8 was indeed not different from the other layers. It was simply the way that layer 8 was exposed by the excavation that was ideal to catch the actual top, middle and base of the shell deposit.

In conclusion, the need for more stratigraphic information in combination with seasonality dara is obvious. The sampling methods in the field need to be improved and layers that could be showing seasonal changes in succession with the order of their spits, should be sampled as such. The fact that it is possible to trace the accumulation of shells during one specific episode of occupation opens up another time scale of questioning. Were these shells deposited by the same persons or group of people? If it was one group, does this quantity of shell equal the quantity of shellfish that they ate during these few months? Was this the only site that they had been to or was there simultaneous harvesting happening close by? If it was the only site, what does this mean for the overall amount of procured shellfish meat and the group size? A range of these questions are discussed in more detail in the following Chapter 8.

7.6 Summary

Building on the modern study (Chapter 5) this archaeological study aimed to assess the possibility of using *C. fasciatus* specimens from a 4,800 year old shell midden as a proxy for palaeotemperature. To assess the seasons of harvest within the site JW1727, 81 shells were analysed of which about two thirds successfully produced seasonal signals. The general trends within the seasonality of the site are an all-year availability of shellfish and an increased exploitation during summer and autumn. The sub-tropical environment and general richness of the southern Red Sea are possible preconditions for both of these trends. On the one hand, these preconditions guarantee marine productivity throughout the year, on the other hand they negatively affect the terrestrial vegetation. The increased aridity during summer and autumn are likely the main cause for an increase in shellfishing during these seasons. Radiocarbon dates indicated, and seasonality data confirmed, a rapid accumulation of *C. fasciatus* deposits, which was most prevalent in layer 8, where individual spits gradually changed the seasons in agreement with their stratigraphic sequence. This makes it possible to assess the accumulation rate on a previously unknown scale for shell midden deposits. Additionally, the use of statistical analysis and statistical validation of shell sequences made the interpretation of the seasonality data more objective. The inconsistency in what growth increments mean for the sequential sampling of shell carbonate for stable isotope analysis is a problem that needs further analysis. But the statistical values for these unclear sequences helped to measure the overall impact on the seasonality study and to quantify how interpretable they are.

Chapter Eight

Evaluating the capabilities of coastal exploitation on the Farasan Islands to sustain human subsistence

8.1 Introduction

In the following I will compare the site composition and accumulation processes at three sites (JW1727, JE0004, KM1057) from different parts of Farasan to assess the general richness of the coastal environment (Fig. 8.1). This section will make use of information about site composition, radiocarbon dates, and seasonality data to evaluate the abundance of coastal resources.

The importance that shellfish had for the diet of the inhabitants of Farasan has been discussed before (Williams 2011). Preliminary calculations of the general availability of shellfish meat were unclear but suggested that the amount of marine food represented in the totality of the middens (then 2811) could support a population of 78 people on a 100% shellfish diet for 600 years or 2,200 people on a mixed diet (40% shellfish) for 300 years. These numbers are open to various interpretations and are depending on varying factors of group size, percentage of shell meat in diet, seasonality and duration of occupation. The various biases and controls for each of those factors have been discussed in detail for sites in California (Erlandson 1988) and Australia (Bailey 1975).

For the two sites analysed by Williams (KM1057 and JE0004) it was evident that the shellfish remains represented by them would not have sufficed to fully support a single person throughout their accumulation periods. This could mean that there are long gaps in the overall site accumulation period or also that the radiocarbon dates are inaccurate. There is no information about how much of the diet consisted of shellfish meat and also no data about the seasonality within the sites.

Some of this information is now available for JW1727 and it might help us to understand how the other sites accumulated. Not only do seasonality data from JW1727 indicate year-round exploitation in almost every analysed layer but also radiocarbon dates indicate a rapidly accumulated midden, which could not have reached its large size if people had only visited it intermittently. Using these additional parameters will change the approximations of accumulation rates and continuity of exploitation. It will also help to gain a better understanding of how intensively sites on Farasan were accumulated in general. Williams (2011) showed that there are large differences between KM1057 and JE0004 with the former one being several times the size of the latter while having occupation periods of similar length. This divide in exploitation intensity was attributed to the two different geomorphologies of each nearby marine environment and probable habitat of the exploited shellfish. With JW1727 being in a mixture of the extensive shallow water environment of KM1057 and the more exposed environment at JE0004, it could bridge this divide and give a better estimate of how the general exploitation intensity on Farasan was.

General information about the site composition of the discussed sites was presented in Chapter 2 for KM1057 and JE0004 and in Chapter 7 for JW1727. As additional information I will look at changes in *C. fasciatus* shell size within each midden to see if they share similarities and if there are changes in subsistence that can be connected to a reduction of marine resources due to human exploitation. Of course *C. fasciatus* does not represent all marine resources of the Farasan Islands and any sign of overexploitation can only be confirmed for this species but it is the mainly targeted species for human exploitation and provides the most detailed dataset available.

The first section of this chapter will give a short overview of the methodological theory when analysing the species composition of shell mounds and will focus on the detection of anthropogenic resource declines (**Chapter 8.2**). Following this, I will discuss the ecological information in the form of shell sizes and species compositions that was gained from the bulk samples JE0004 and KM1057. This is then put into a context with the data from JW1727 (**Chapter 8.3**). The section concludes with new data on food availability throughout the year at each site with a focus on comparing accumulation rates based on radiocarbon dates and seasonality data (**Chapter 8.4**).

8.2 Site composition and possible ecological changes within archaeological sites

Because the shell mounds are mainly the results of what people ate, they are intrinsically connected to the ecology of their food source. By analysing the characteristics of the consumed food, we can draw some conclusion about the relationship between the people of Farasan and the marine food sources. The large scale exploitations of the Farasan shell mounds might lead us to expect some human impact on the food supply. Even today, the phenomenon of over-fishing or over-harvesting certain food sources is common; one of the reasons why the Farasan Islands are now a marine sanctuary (Gladstone 2000).

The effects of overexploitation in archaeological contexts have been the subject of a number of studies (Broughton et al. 2010, Butler 2001, Butler and Campbell 2004, Grayson and Delpech 1998, Mannino and Thomas 2001, Morrison and Hunt 2007, Nagaoka 2002). The general signals for a reduction in resources because of human exploitation are a decrease in encounter rates with the exploited prey and a decrease in the general abundance of the exploited prey reflected in the size and age distribution of the population. This happens because the human predation is more efficient than the reproduction of the targeted animal.

These effects are being discussed in optimal foraging theory. The theory assumes that to fulfil a specific aim (often to reach the daily caloric intake) organisms will find an optimal strategy depending on the prey, the time and effort investments, the payoff, and the environmental restraints. Following this theory, when an already optimal resource becomes scarcer because exploitation is higher than reproduction, the former optimal strategy of humans adapts to the new situation and incorporates a different prey, wider areas of exploitation, or better techniques of predation (Lupo 2007). A diet breadth expansion is carried out and targeted food sources can be different from the earlier diet and can show up as a change in the composition of shell mounds. This can be the species composition but also the composition of different sizes of the same species. As the exploitation by humans continues, the animals have less time to grow into older ages without being eaten first. Human predation will generally focus more on the older and bigger animals as they generally bear more meat. This will shift the mean age towards shorter lifespans and the mean size towards smaller sizes as well as skew the age/size distribution.

One aspect of this connection between age and size has been discussed by several researchers (Campbell 2008, Claassen 1998, Giovas et al. 2010, Mannino and Thomas 2001, 2002, Milner et al. 2007, Roy et al. 2003). In some cases, the decline in mean size is caused by environmental or pathological factors without having an affect on the overall age of the population. It follows that to really know if there is an anthropogenic resource depression causing a shift of the mean size, it needs to be shown that the mean age is similarly decreasing because it is not an important factor of the human selection process.

In the case of *C. fasciatus* an assessment of the age structure of the population is difficult. The lack of research of modern specimens prevents any clear estimations. Also the species does not have any age indicators beyond an adult lip, which is almost always present in the archaeology material (Eva Laurie, pers. comm.). This lack of specimens without adult lips indicates that there has been some selection of larger specimens and that the exploitation of juvenile specimens did not happen. Whether intentional or not, the exploitation was restricted to larger, reproducing animals, meaning smaller, adult specimens were still able to reproduce. Otherwise the overall potential for reproduction and sustaining the *C. fasciatus* population would have been heavily impacted because all mature animals would be removed (Fenberg and Roy 2012, Lasiak 1991, Mannino and Thomas 2002).

Interestingly, if only large animals are being targeted and small specimens can reproduce freely, then the phenotypically smaller animals might be favoured over long periods having a genetic impact on the overall population (Fenberg and Roy 2007, Law and Stokes 2005). However assessing this in the archaeological record from Farasan is beyond the remit of this project.

Another type of change in the composition of shell mounds is the switch from food sources that are easy to find and to process and also bear a lot of meat towards food sources that are less easy to find, more difficult to process and bear less meat. Because the former kind of sources is becoming less abundant, the latter become more and more necessary. In the case of the Farasan shell mounds it is already obvious that *C. fasciatus* specimens are one of the main food sources even though they don't bear a lot of meat. This is not uncommon. Depending on the abundance and the harvesting technology it can be easier to collect many small individuals rather than one big individual (Cannon 2000, Grayson and Cannon 1999).

Following these observations, I will inspect the three sites (KM1057, JE0004, JW1727) for general signs of decline in the *C. fasciatus* resources expressed as, 1). Lower percentage of *C. fasciatus* shells within the layer, 2). Decreasing mean sizes of *C. fasciatus* shells 3). Positively skewed size distributions of shells.

As already mentioned, the environmental restrictions, more or less favourable habitats, or the number of predators in the vicinity can have impacts on the shellfish population besides human exploitation. These factors need to be ruled out or at least considered and discussed before jumping to conclusions.

8.3 Site compositions of different Farasan shell mounds

8.3.1 Methods of analysis

The data that is discussed here is based on the analysis of column samples carried out by Eva Laurie and Matt Williams (Laurie unpublished, Williams 2011). As the data is unpublished, excerpts of it that are being discussed here can be found in Appendix 5.

As previously described for JW1727 (Chapter 2, 7), the bulk samples were taken in column by layer and in 10 cm spits where necessary. Each fraction of the material was analysed and shells that had diagnostic features were sorted, counted, measured, and recorded to determine minimum number of individuals (MNI) and shell weight. Comparing the trends in shell size, MNI and weight within the shell mounds but also between the sites can provide insight into the impact that shellfish exploitation or environmental changes had on the marine resources over long-term and short-term episodes. Because the overall shell length of gastropods can be estimated by measuring the outer lip (Dépraz et al. 2009) the shell size of *C. fasciatus* shells is here presented as the length of the adult lip ("Aperture size") (Fig. 8.2).

The size measurements from the analysis of bulk samples from JW1727 carried out by Eva Laurie were similarly acquired. Overall 5837 shell apertures from the three sites have been measured via digital callipers to two decimal places.

8.3.2 KM1057

As mentioned earlier (Chapter 2), the KM1057 shell mound is a shell deposit of large size (~900 m^3). The site is composed of predominantly *C. fasciatus* shells (81%) and has been rapidly accumulated over a short time period (382 years, Williams 2011). The following section will provide a more detailed analysis of the shell species composition of the site and will especially focus on the changes in *C. fasciatus* size provided by the measurements of the aperture.

The general composition of KM1057 remains unchanged throughout the column with only two interruptions of the *C. fasciatus* dominance by *Chama reflex* and *Spondylus marisrubi* layers at 20 cm depth and 250 cm depth (Fig. 8.3). However, the shell size shows significant differences and trends throughout the section (Fig. 8.4). Notably, the top layers of the midden (Unit A, layer 204-201) show a reduction of shell size that is coinciding with a *C. pacifica (also reflexa)* and *S. marisrubi* layer (207) followed by two layers of small-size *Conomurex fasciatus*. Additionally, another more gradual but significant decline of shell size was found over a bigger period (Unit B, layers 217-

210). Connected to this, a distinct decrease of shell size was found half way through the section (Unit C, layers 304-306), followed by a sharp increase in the layers above (layers 307-309).

The first instance of shell size change in unit C (layers 304-309, Fig. 8.3) was preceded by a more or less stable constant exploitation of *C. fasciatus* (layers 293-291), that even during the collection of other shellfish species did not completely fade (Fig 8.4). The beginning of unit C sees a change in aperture size distribution with a change in means from 23.6 mm (layer 304) to 21.5 mm (305) (Fig 8.5). This change was analysed using a Mann-Whitney U test resulting in a highly significant p-value of $p=1.06*10^{-11}$.

This is followed by a less significant decrease (p=0.052) from layer 305 to 306, the layer with the lowest average aperture size (21.01 mm) in the whole midden. This is followed by a decline of *C. fasciatus* in terms of shell weight (layer 307) and a gradual increase ($p=1.47*10^{-7}$) of shell size (307, 308, 309). At the end of this increase, which also resulted in the layer with the highest average shell size (309, 25.13 mm), shell weight per sample of *C. fasciatus* reached the previous value of 1,300 g.

How extreme this change in shell size distribution in comparison to the site-average is, is shown in the cumulative size distribution of each spit (Fig 8.5 D). Spits with smaller shells are shown in red and orange, while spits with larger shells are coloured in dark and light blue. The site-average was calculated using each of the 3,064 size measurements within KM1057.

How much time passed between the minimum (306) and the maximum (309) mean of aperture size, is not known. The radiocarbon dates from the top and the bottom of the midden indicate that it was likely to be less than century (Williams 2011). The influence of sea level change is a likely cause for a decline in *C. fasciatus*, whose richness is possibly linked to the shallow marine environment that is Khur Maadi Bay (Chapter 2, Fig 2.7.3.6). Extreme tidal activities or dry periods could have caused a temporary sea level drop in the bay or resulted in sediment infill or erosion, with dramatic causes for the shallow water ecosystem.

An abandonment of the site because of the small size of available *C. fasciatus* is also questionable, considering the availability of other shell species (*Chama pacifica, S. marisrubi*). Could the subsistence strategy and general mobility be so dependent on the gathering of *Conomurex fasciatus*? Also, as I show further below, the aperture sizes within spit 306 are still far above the average of other sites (JE0004). It could mean that the size changes from 306 to 309 are not actually that dramatic.

A more gradual change was found in unit B over the course of 10 spits within the centre of the midden (Fig. 8.6). The species composition in this area is never lower than 95% *C. fasciatus* and the weight of *C. fasciatus* per sample is fairly constant between 1500 g and 2000 g with only a slight increase (Fig. 8.5). However, the mean aperture size of *C. fasciatus* is following a decreasing trend throughout the deposit stretching over 70 cm. The gradual trend is only slight from one spit to another but highly significant when comparing spits that are further apart on the gradual decline. A Mann-Whitney U test of spits 310 and 206 that was corrected via the Bonferroni method resulted in a p-value of $p=0.046$ (uncorrected: $p=5.83*10^{-5}$). In particular, the cumulative distribution of shell sizes (Fig. 8.6) shows the gradual change of spits with higher amounts of big shells (blue) in comparison to the overall site-average towards spits with relatively small shell sizes (green).

Comparing this gradual change in shell size to the more rapid one in unit C, it is more likely that the gradual change is more indicative of the exploitation strategy that was followed at KM1057. While the earlier scenario could have also been the result of an event with an environmental cause, the declining trend found in this part of the midden is likely the result of a long-term development that is statistically significant over a more constant direction towards smaller shell sizes. It is more likely that this trend is the cause of an exploitation technique that has been used for longer periods and put constant pressure on the *C. fasciatus* population, which was not directly noticeable but had an impact over a longer period.

Regardless of this impact on the shell size, the amounts of *C. fasciatus* do not change significantly, suggesting that the change was not big enough to stop targeting this species. The MNI and weight in the following spits (209-204) has increased (Fig. 8.4). The mean aperture size has a recovery from 22.08 mm (spit 210) to 23.20 mm (spit 209). A Mann-Whitney U test resulted in a significance of $p=1.189*10^{-4}$. If there has been a hiatus between the two spits or if other causes are responsible for the sudden increase in shell size, like a different collection area with an untouched population, is not clear.

Unit A (Fig. 8.7) is again mostly made of *C. fasciatus* shells but also characterised by the remains of a hearth and a distinct layer of *Chama pacifica* and *S. marisrubi*. In comparison to the earlier concentrations of bivalves at the base of the midden, where there was still a large amount of *Conomurex fasciatus* to be found, in the unit A the bivalve layer has a much higher concentration of *Chama pacifica* and *S. marisrubi* and only very little *Conomurex fasciatus* (4.8%, 67 g). The layers above the hearth area (203, 204) have again very large amounts of *C. fasciatus* shells, and an average aperture size of ~23 mm. This is followed by the highly concentrated bivalve layer (207), accompanied by a significant decrease of aperture size that carries on into the top layers of the midden (201,202). Results of a Mann-Whitney U test and subsequent correction by Bonferroni method resulted in a significance value of p=0.0039 (uncorrected p=4.95*10$^{-0.6}$). Despite this interruption, the weight of *C. fasciatus* in the samples gradually increased in the top spits (201, 202) and reaches the usual value of ~1500g again. Similar to unit C, it is possible that these few spits following a rapid decline in aperture size cover a longer time period than the ones before. In contrast, in unit C the mean aperture size rose again to 25.13 mm (309), while in unit A it remains lower at 22.24 mm (201).

It is possible that the lower shell sizes are connected to the abandonment of the site. Williams (2011) argued that the uplifted bay area and the subsequent deterioration of the marine environment was a possible cause for the decline of *C. fasciatus* populations and for other shellfish species, which led to an end of shellfish exploitation at KM1057. When this uplift and the sea-level change in Khur Maadi Bay happened is not clear. The difference in aperture sizes in the top three spits (201,202, 207) and the two below (203, 204) indicate that if there was an environmental change that led to a devastating change of the marine environment, it was likely to have started to have an impact between the times of deposition of these two groups.

In sum, the changes throughout the sample column of KM1057 show short term and long term trends of *C. fasciatus* exploitation. It is not possible to directly link them to environmental changes, anthropogenic resource depression by intense exploitation, or the general movements of the groups gathering the shells. However, there are some conclusions that can be drawn. The subsistence is obviously targeted on *C. fasciatus* rather than any other shellfish species. Evidently, there are other species (*Chama pacifica* and *S. marisrubi*) in the midden but the reason for their collection is not clear. Occurrences of alternative species linked to changes in *Conomurex fasciatus* size have been found as well as occurrences during no changes of *C. fasciatus* size or weight. Clearly, the reason for the collection of alternative shellfish species is not necessarily linked to the lower meat yield of small *Conomurex fasciatus*. It might be caused by non-subsistence related activities like tool-making but also simply be personal preference of the collectors.

Two kinds of changes in the size of *C. fasciatus* were found, with one kind happening over the period of deposition of numerous layers (unit B) and one kind happening over the period of only a few layers (units A and C). I am inclined to interpret the more gradual change as an indicator of anthropogenic population pressure and the more abrupt ones as the result of environmental change in the form of an event that affected the whole of Khur Maadi Bay. If the gradual changes are happening over a long-term and the abrupt ones over a short-term cannot be said. I can only analyse the changes from one layer to another and the radiocarbon dates do not allow enough resolution to check for hiatuses in between them. Obvious increases in aperture size could be accompanied by abandonments of the site. This can imply that *C. fasciatus* was so favoured that other collection areas of *C. fasciatus* were targeted, rather than other species. However, environmental change that influences C. fasciatus size or availability is likely to equally influence other species, making a site abandonment completely unrelated to shell species preference.

8.3.3 JE0004

As a re-assessment and as comparison to other shell mound sites around Janaba Bay, the ecological processes at JE0004 will be analysed in more detail. The site is of similar size as JW1727 but has been occupied for a much longer time period (Chapter 2). The long occupation period in combination with the small size is an indicator that the accumulation of shellfish did not happen as intensively as it was seen in KM1057.

The following section provides a concise analysis of the shell species composition of the site and focusses especially on the changes in *C. fasciatus* size provided by the measurements of the aperture.

Because of the complex nature of the stratigraphy of JE0004, I chose to analyse only one of the columns (11G) (Fig. 8.8). Specifically, 11G is a column that covers early parts of the midden as well as the later phase which covers the northern parts of the midden, which also include pockets of fishbone (see chapter 2 for more detail).

The column has not been analysed completely but the data covers most of the sequence with only a few gaps in between. The composition of the layers varies notably with the most abundant species being *C. fasciatus*, *Pinctada* sp., *Chicoreus* sp., and *Chama* sp. (Fig. 8.9). The amounts of *Conomurex fasciatus* become more dominant in the higher parts of the column (layers 1-48) together with *Chama* sp., while *Pinctada* sp., *Chicoreus* sp., and *Spondylus* sp. are more dominant in the lower layers (51-56). This divide is also found in the mean aperture sizes of *C. fasciatus*, which start at 20.5 mm (54-56) and end at 18.9 mm (1). The overall mean aperture size is 19.4 mm, much smaller in comparison to KM1057 (22.9 mm).

The relatively short column shows less change than what was found in KM1057. This is partially due to the complexity of the site in general, which made it necessary to combine some of the bulk samples and generally makes it difficult to compare the overall trends. Because of the different sizes of samples, I also used the weight percentage in the above diagram, rather than the absolute values, which can be found in Appendix 5.

In a simplified way, Fig. 8.10 shows the change of *C. fasciatus* weight in comparison to aperture sizes. For some bulk samples (684 and 672) no aperture size data was available, which is why they do not show up in this part of the analysis. Despite these restrictions, it was possible to further analyse the change in size of *C. fasciatus* between the early phases of the midden and the final phases. The size distributions throughout the column are fairly un-skewed, where the number of analysed specimen permits analysis. Unskewed distributions could indicate a lack of stress onto the population. However, there is a gradual change from bigger sizes towards small sizes, that is visible from layers 51 and 52, towards layer 3. A Mann-Whitney U test and subsequent Bonferroni correction resulted in a significance value of $p=4.04*10^{-11}$ (uncorrected value: $p=1.44*10^{-12}$).

If it was environmental change that caused the decrease in shell size, as suggested by Williams (2011), or the more intensive exploitation of *C. fasciatus* is unclear. Evidently, the area in front of the site where the shells were most likely to have originated from is still submerged and the steeper slope than the one in Khur Maadi Bay makes it less susceptible to tectonic uplift. In the vicinity of JE0004 there is a shallow water area but it only stretches ~60 m. After that the water depth reaches to 1.5 m to 2.0 m and there is a significant drop beyond a coral reef (Chapter 2, Fig. 2.3 and 2.9).

Interestingly the change in shell size is showing a negatively correlated trend to the weight percentage within the layers (Fig. 8.11). In other words shell size appears to decrease as the proportion of *C. fasciatus* increases. This relationship ($R^2=0.81$) could indicate some degree of connection that the exploitation of *C. fasciatus* has on the shell size. However, if this is happening here is hard to say without more data points and what it could mean for the exploitation patterns at JE0004 is unknown.

Generally, the species composition at JE0004 is less focused on *C. fasciatus* and includes many other shellfish species. If this diversification was necessary to make shellfish gathering sustainable or even profitable, is not clear. Equally it could be an indication of species diversity and accessibility in the local marine environment that is found here but not in places like KM1057. In Janaba Bay other shellfish species could have been more abundant than in Khur Maadi Bay allowing for a different exploitation strategy, which is also indicated by the occurrence of fishbone pockets. In comparison, KM1057 has a very simple composition of chiefly *C. fasciatus*. Could it be that the lack of other species is also the reason for the big difference in shell sizes between both bays? None of the mean aperture sizes of *C. fasciatus* in JE0004 reach the mean values found in layers of KM1057. A comparison of size measurements from other shell species found in both sites could help to solve this questions. If there is a general difference in species size, it is quite possible that the large subtidal bay area of Khur Maadi Bay creates a more protected habitat that is less exposed to the open sea. For now the large sizes of *C. fasciatus* apertures at KM1057 demonstrate a generally more sheltered marine environment at Khur Maadi in comparison to Janaba East, which is applicable to all species. From this it can be assumed that the ecological information from column 11G in JE0004 indicates a far less productive marine environment than the one represented in KM1057.

8.3.4 JW1727

Following the results of KM1057, which was dominated by layers of big *C. fasciatus* shells, and the comparatively mixed shell mound JE0004 with smaller shell sizes, the analysis of JW1727 can help to understand both of them through its similar geomorphological backgrounds and composition. KM1057 is next to an enclosed shallow water area between the two main islands, Saqid and Farasan Kabir, and JE0004 is at an undercut cliff in the eastern part of the more exposed Janaba Bay. A mixture of both can be found at JW1727, which is located at the edge of an uplifted shallow bay area of similar size as Khur Maadi Bay but it is also part of Janaba Bay which is much more exposed than Khur Maadi Bay (Fig. 8.12). This means that the character of the marine environment in the vicinity of JW1727, is likely to be a mixture of what was found at KM1057 and JE0004. An open, more diverse environment, but with a conveniently shallow water depth that makes shellfish collection more efficient and potentially offers a much larger habitat to exploit. The different time scale in which JW1727 was accumulated will provide a higher resolution of the exploitation patterns and processes on Farasan in general. KM1057 and JE0004 both have minimum accumulation times of several hundred years, while for JW1727 this happened in a matter of decades (Chapter 7).

As mentioned before, JW1727 mostly consists of *C. fasciatus* shells (72% of weight) and has distinct layers of bivalves (*Begunia gubernaculum* and *Pinctada* sp.), mixed layers (*C. fasciatus* and *Arca avellana*), as well as hearth deposits (Fig. 8.13). Despite this, *C. fasciatus* can be found in every single layer and is, apart from layer 3, always the most dominant species (Fig. 8.14).

Aperture size measurements show a different picture than what was visible in KM1057 and JE0004. The average aperture sizes range between 20.0 mm and 22.3 mm (average apertures sizes in KM1057: 22.9 mm , JE0004: 19.2 mm), which fits well between the two other sites, but the variation between the mean sizes per layer is smaller (JW1727:0.54 mm, KM1057: 0.74 mm, JE0004: 0.58 mm), this makes it more difficult to analyse patterns throughout the column and more difficult to look for trends or correlations between aperture sizes and layer composition. Interestingly, layers with small amounts of *C. fasciatus* do not have a distinctively different aperture size, as has been visible in KM1057, where small amounts of *C. fasciatus* were correlated with smaller apertures. There are no obvious hiatuses in shell accumulation as observed at KM1057. This is consistent with the evidence at JW1727 for uniformity in the relative proportions of *C. fasciatus* and uniformity of aperture sizes.

The different frequency distributions of aperture sizes show no clear trends but more an ever changing composition with more or less normally distributed values. Some are skewed positively (4, 7, 11, 16, 17) but this is far from being indicative for overexploitation. Layer 8 stands out with a platykurtic distribution with few specimens with extreme aperture sizes below 20 mm or above 24 mm. The reason for this concentration of medium sized shells is not apparent and not discernibly linked to any other measurement of this layer.

More accessibly, the aperture size distributions are presented in the form of cumulative distribution graphs (Fig. 8.15). Because of the lack of variation in shell size between the different layers, the cumulative graphs have been divided into layers with smaller mean values and layers with higher mean values than the overall site average. It appears that the layers with by far the biggest shell sizes (8, 24, 26) are close to the mean of KM1057. Layers 24 and 26 are sand layers with mixed in *C. fasciatus* shells of unknown context. They could be mixed in from layer 23 but are far too big for it. It is more likely that they are the remains of earlier, less preserved shell accumulations that have been reworked into the beach sand. Their larger size could be due to a pristine shellfish population without any pressure due to intense exploitation. The lack of a more gradual decrease from then to layer 23 could be explained with exploitation taking place but being recorded somewhere else. As mentioned before, JW1727 is not the only shell mound in this area and changes like this could well have been recorded in other shell mounds that started to accumulate before the start of layer 23.

Testing the significance levels of changing frequencies of shell size within each layer using Mann-Whitney U tests with Bonferroni corrections, it appeared that a significant change stretching from layer 22 to layer 16 took place ($p=0.0025$). Layer 22 is the first layer almost completely made of *C. fasciatus* and is likely to be the first instance of intense exploitation happening in JW1727. The layers above (20, 19, 18, 16) are also pure *C. fasciatus* layers apart from layers 17 and 21, which are also to a small degree made of *Begunia gubernaculum* and *Arca avellana* shells. This set of layers shows a gradual decline in aperture size from 21.3 mm to 20.4 mm (Fig. 8.16). The change is very small but it is hardly questionable. I am inclined to interpret it as the result of a more or less constant subsistence strategy that allows the sustainable exploitation of *C. fasciatus* without a dramatic impact on the mollusc population to the degree that it is detectable through a noticeable decrease in individual shell size.

Additionally, from the seasonality data of JW1727 we know that layers 18, 20, and 22 were all accumulated throughout most of the year and more often during autumn and summer (Chapter 7). In this respect they are in agreement with what has been found in the rest of the midden, suggesting some degree of stability and of sustainability.

However, why this trend of decreasing shell size came to an end in layer 15 is not clear. The layer colour changes in layer 14 for no apparent reason and the otherwise clean *C. fasciatus* shells become orange. The amounts of charcoal and ash layers in the upper parts of the midden increase in comparison to the lower parts. This might be connected to different processing techniques taking place, or different activities in general.

To sum up, the analysis of shell size in comparison with species composition of different layers has put JW1727 fairly well between the results from KM1057 and JE0004. The shallowness and the extent of the marine environment in the vicinity of JW1727 has provided a rich coastal resource, which has probably been used for longer than the short occupation period of JW1727.

The aperture size values of shells, exploited or natural, that were reworked into the beach sediment below the mound indicate a more beneficial environment for *C. fasciatus* shells. After the initial drop in shell size, values stabilised, while *C. fasciatus* exploitation continued. Still, several anomalies in the record remain unexplained. The distinctively different distribution of aperture sizes in layer 8 as well as their generally large size is enigmatic. That this layer is also unique in terms of its seasonality data and its rapid accumulation is possibly a reason for this but not discernibly linked. There is no obvious reason why a rapid accumulation should be associated with larger shells and the rapidness of the layer relative to the other layers could not clearly be assessed (Chapter 7.5). It could well be that it is not as unique as the seasonality data suggests.

In the end the high temporal resolution and the short time scale gained through the rapid accumulation of JW1727 in general could be a reason why some aspects of the shell mound remain cryptic and big events like hiatuses and the differences before and after, which are apparent in longer-term records, are being missed by short occupations like this. It is the lack of obvious hiatuses and the possible non-existence of long-term abandonment that make JW1727 an interesting source for ecological datasets. It shows definite traces of stability and a sustainable subsistence strategy over several decades.

8.3.5 Summary

In conclusion of this section, it was shown that there are definite changes in shell sizes and species composition within each shell mound. Their compositions are, although dominated by *C. fasciatus*, different from each other because the sites are the products of their coastal environment. Since each location has its own kind of geomorphological characteristics, it is not surprising that each one has its own kind of species composition.

Additionally, shell sizes of *C. fasciatus* differ from one site to another but remain fairly similar within one assemblage (Fig. 8.17). Since the differences between the sites are bigger than the differences between layers of the same site, it is unlikely that the size differences between sites are chiefly linked to anthropogenic resource depressions but rather to factors that influence all sizes, like the geomorphology of the collection area. If the case was that anthropogenic resource depression was the main cause of small shell sizes, then the shells would have been less intensively exploited at KM1057 than at JE0004. This is not reflected in the total amounts of shell preserved as JE0004 would need to be much bigger and KM1057 much smaller. Alternatively, the exploitation at KM1057 could have impacted on the *C. fasciatus* population represented by JE0004. Because of the distance between the sites, this is highly unlikely.

Again, the differences are likely to be linked to the different geomorphology of the coastal environment the sites are in. Because the shellfish grew bigger in the favourable environment of Khur Maadi Bay, they were preyed on more frequently and in bigger proportions. This resulted in larger average sizes of *C. fasciatus* found in KM1057. If this richness is the case for all sites in Khur Maadi Bay can only be answered by additional excavations. It might well be the case that other sites at Khur Maadi Bay show smaller aperture sizes and higher percentage of other shell species.

Geological data also tells us that the geomorphology of the Farasan Island has been extremely variable in the past (Bantan 1999). Preliminary work by Williams (2011, see also Meredith-Williams et al. 2014) showed the changing coastline at Khur Maadi and suggested that the eventual uplift of the area must have had a serious impact onto the exploitation of *C. fasciatus*. However, a similar picture was not found at Janaba Bay, where the shallow water area was available for much longer than the period of intensive exploitation.

In the future, a better understanding of the geomorphological change of the Farasan Islands during the mid-Holocene will likely help to quantify the influence of the shallow water areas on the marine wildlife and the link to human occupation. Centres of shellfish gathering that are targeted towards *C. fasciatus* and other areas where more mixed gathering strategies are applied are clearly noticeable on Farasan. None of the aperture size measurements showed signs of clear anthropogenic depression of *C. fasciatus* to the degree that the resource is depleted.

Even though there are signs of human exploitation impacting on the shellfish population, the whole of the shellfish gathering processes seems sustainable. In addition with the seasonality data from JW1727 (Chapter 7) this indicates a consistent use of the sites and that the sites were to some degree able to reliably support its people with enough food for longer periods. How this connects to earlier calculations of meat availability will be discussed in the next section.

8.4 Shell accumulation and meat availability

8.4.1 Introduction

In the previous chapters (3,7) I have argued that seasonality data are a good proxy for the ecological aspects of coastal subsistence, but they can also be used for the analysis of accumulation rates and to quantitatively reconstruct the shellfish availability. In this section I will compare previous research on shellfish exploitation on the Farasan Islands (Williams 2011) with the new dataset from JW1727 and will discuss the use of sequential seasonality data from a single layer to explore accumulation rates on a smaller scale than what was previously possible through radiocarbon dates. The results will better our understanding of how sustainable permanent living on the Farasan Islands was and how much the subsistence of people also depended on other food sources than shellfish.

There is particular interest in the amount of food that the shell refuse represents (Bailey 1975, Erlandson 1988, Erlandson et. al 1999, Hildebrandt et al. 2009, Meehan 1977). For shellfish remains in general it has also been argued that they were not in fact a food source but used as bait for fishing. Milner et al. (2007) proposed this after analysing the limpet remains and the fish remains at Quoygrew, Orkney. They found a correlation between the increases of exploitation intensities in both groups. The percentage of remains grew together rather than one group displacing the other, which would indicate a change in subsistence from one food source to the other. While this does not necessarily mean that limpets were only used as baits, it is a good explanation for the simultaneous increase in both resources.

Even though there has not yet been a sufficient analysis of the fish remains from Farasan shell mounds, there are several arguments against interpreting *C. fasciatus* as bait in JW1727. Firstly, the gathering and processing of the mollusc is extremely simple and the meat easily acquired, making it an ideal food source. Also the amount of *C. fasciatus* shell remains in comparison to other shells or fish bone would point towards the use of *C. fasciatus* as an important protein source if not the main protein source. Additionally, to get raw *C. fasciatus* out of the shell and use the meat as bait, one would need to cut the mollusc from the carbonate shell. Since the mollusc is attached to it all the way up into the apex, this is a very difficult task and even with modern equipment a strenuous exercise. Only cooking the animal makes it easy to detach it from its shell.

The possibility of using cooked *C. fasciatus* as bait does exist but seems pointless as there is an even easier way to get to the meat. Modern fishers do occasionally use *C. fasciatus* as bait together with other shellfish. They avoid the inconvenient extraction of the meat by crushing the whole animal in its shell and taking the mollusc meat out of the shell remains (Fig. 8.18). This is a technique that would also have been available in prehistoric times and would be found in shell middens in the form of crushed shell remains (Rivera-Collazo 2010). Crushed shell remains rarely occur in the Farasan shell mounds (Alsharekh and Bailey 2014). Also, where they do occur it is not clear if they are signs of people preparing bait or if they are signs of abandonment (Sullivan 1984). A more detailed analysis of the general weathering of crushed shells might help to answer these issues.

Also the fish remains need to be analysed to get a better idea of how molluscs were used at JW1727. The amount of excavated fish remains is very small and may indicate that they were not eaten on a big scale. However, differently to other excavations on Farasan (Williams 2011), the sieving techniques used on site did not use sufficient mesh sizes to recover all fish bones (1-2 mm), which will to some degree account for the small assemblage (see Cannon 1999, Claassen 2000, Giovas 2009, Zohar and Belmaker 2005).

Since the actual use of the middens might be restricted to shellfish processing (Bailey et al. 2013), the processing of fish could easily have happened at different locations with bad preservation conditions, so that the fish remains are simply not preserved. Keeping these taphonomic issues in mind, the *C. fasciatus* remains will be interpreted as a food source, rather than bait because of its ease of acquisition and simple processing.

8.4.2 Previous results

Williams (2011) makes preliminary assumptions of how much shell meat is represented by the Farasan Island shell mounds and calculates how many people could be sustained with this food source over the total period of occupation using groups of 1, 5 and 10 people. He uses the species composition of two sites (JE0004 and KM1057) to estimate the amount of meat available per day and extrapolates this to their spatial clusters and subsequently to all of Farasan. He uses two diet models based on observations by Meehan (1977). One mixed diet using 0.6 kg of shell meat per day as main source of protein and supplements this with other food sources (0.5 kg carbohydrates and 0.4 kg vegetables). The other diet is more theoretical. It only consists of shell meat to cover the daily caloric intake, which is an equivalent of 2.4 kg of shell meat. He acknowledges the simplicity of the model and its obvious flaws, among them the assumption of similar species composition for every mound, similar mound sizes and overall occupation period of 300 to 600 years based on the radiocarbon dates of JE0004 and KM1057. Nevertheless, the conclusions he found are interesting. Despite their sizes of several hundred cubic metres, they could only sustain a group of 5 people for only a fraction of a year. This is due to their long period of occupation of a minimum of 328 years (JE0004) and 382 years (KM1057). Even when extrapolating the results to the whole of the surveyed middens (n=476) and over a period of 600 years based on the radiocarbon dates of the two mounds, the amount of shell food would only be able to sustain 78 people all year round.

JE0004	**Meat per day**	**Occupation period**		**Days per year (1 person) for:**		**Days per year (5 people) for:**		**Days per year (10 people) for:**	
Diet		Days	Year	328 yrs	511 yrs	328	511yrs	328 yrs	511 yrs
Shellfish	2.4	8,625	23.6	26.3	16.9	5.3	3.4	2.6	1.7
Mixed	0.6	34,500	94.5	105.2	67.5	21.0	13.5	10.5	6.8
Total meat	20,700								

KM1057	**Meat per day**	**Occupation period**		**Days per year (1 person) for:**	**Days per year (5 people) for:**	**Days per year (10 people) for:**
Diet		Days	Years	382 yrs	382 yrs	382 yrs
Shellfish	2.4	37,583	103	98	20	10
Mixed	0.6	150,333	412	394	79	39
Total meat	90,200					

Table 8.1 Duration of site occupation based on amount of shellfish meat at site after Williams (2011, table 23 and 24).

8.4.3 Updated results

In comparison to this earlier research on the amount of shellfish meat from Farasan shell mounds JE0004 and KM1057, I will use the volumetric data and general composition of JW1727. Also the relatively fast accumulation of the site might provide a closer view of the general shell accumulation. Similar to Williams (2011) the estimated volume (163 m^3) is based on a simplified model of JW1727, where the site is treated as a truncated cone with a lower radius of 8 m and an upper radius of 1.5 m based on field observation. Unlike Williams, I simplified the calculations by defining *C. fasciatus* shells as the only component of the mound and do not take other shell species into account. This is not too far from the species composition of the site with 83% *C. fasciatus* and works with the calculations of Williams as he uses the same meat to shell ratio for all the species. Based on field observations by Williams, the 163 m^3 are equivalent to 16,300 kg of shell weight. Williams approximates the weight of meat per shell at ~10% (0.7 g). However, my own measurements of cooked modern *C. fasciatus* specimens resulted in ~30% (2.5 g) of meat weight per specimen, producing a total weight of ~48,900 kg of shell meat in JW1727. Table 8.1 shows the estimates for days of shellfish availability from Williams (2011, tables 23 and 24). When applying these data to the new measurements for meat weight, a much more productive image of shellfish exploitation becomes evident (Table 8.2).

The new estimates for total amount of meat are not simply the tripled amounts of meat but are based on the overall composition of the mound (Chapter 8.3.2). These calculations were made to also gain information about the differences between mound volume with and without sediment and to get an estimate for the volume of KM1057. This it is not reported in Williams (2011) but it is necessary to calculate estimates for rates of shell accumulation. The result is similar to the tripled values of the previous estimates and does not introduce any significant errors. Even better, any rounding errors can be ruled out.

JE0004	Meat per day	Occupation period		Days per year (1 person) for:		Days per year (5 people) for:		Days per year (10 people) for:	
Diet		Days	Years	328 yrs	511 yrs	328 yrs	511 yrs	328 yrs	511 yrs
Shellfish	2.4	26,125	72	80	51	16	10	8	5
Mixed	0.6	104,500	286	319	205	64	41	32	20
Total meat	62,700								

KM1057	Meat per day	Occupation period		Days per year (1 person) for:	Days per year (5 people) for:	Days per year (10 people) for:
Diet		Days	Years	382 yrs	382 yrs	382 yrs
Shellfish	2.4	110,239	302	289	58	29
Mixed	0.6	440,956	1,208	1,154	231	115
Total meat	264,573					

JW1727	Meat per day	Occupation period		Days per year (1 person) for:		Days per year (5 people) for:		Days per year (10 people) for:	
Diet		Days	Years	16 yrs	82 yrs	16 yrs	82 yrs	16 yrs	82 yrs
Shellfish	2.4	20,375	55.8	1,273	248	255	50	127	25
Mixed	0.6	81,500	223.3	5,094	994	1019	199	509	99
Total meat	48,900								

Table 8.2 Duration of site occupation based on new amount (30%) of shellfish meat at site.

As expected the assumed days of occupation within one year for JE0004 and KM1057 have virtually tripled. This has a major impact on the amount of days per year when shellfish meat would have been available. What was previously expected to be a marginally efficient coastal landscape that can only provide shellfish meat for 78 people over a long period, is now much more productive. This is mainly due to the improved weight estimates for meat per kg of shell. With the new weights it is much more likely that small groups on a mixed diet were able to live off the amounts of shellfish that could be exploited at one site.

There is a striking difference between the days that shellfish is available per year at JW1727 and KM1057, and at JE0004. The values for the first two sites are much higher than for the last. This suggests that the relationship between accumulation period and accumulated material, the accumulation rate, is similar in JW1727 and KM1057, while the accumulation rate in JE0004 is much lower. In this context, the extremely brief occupation period of JW1727 (16-82 years) seems less of an rarity, as it is possible that KM1057 accumulated just as much shell material per year. The stratigraphic sequence of JE0004 clearly shows some degree of inconsistency in coastal exploitation in the form of a change in species composition. This could also be associated with a hiatus and a period of abandonment, which would have a big influence on the averaged data above. It is difficult to actually get a 'realistic' estimate for what was available within one year because the above data are estimates from sites that have a longevity of hundreds of years based on radiocarbon dates.

The dataset from the seasonality study of JW1727 can help to improve these data and to answer the questions of food availability at a higher temporal resolution and for a time frame that is closer to the day-to-day activities which led to the shell mound accumulation.

8.4.4 Seasonal accumulation

To compare the accumulation rate based on radiocarbon dates with the accumulation rate based on seasonality data, I will use the seasonality results of layer 8 (Chapter 7) and basic calculations for the layer volume to approximate the amount of shellfish meat that was 'realistically' available per day over the accumulation period of layer 8. The sequential stable oxygen isotope values of shell edges in layer 8 showed clear grouping in correlation with the stratigraphic sequence, indicating that the summer values at the base of the layer were deposited first, then followed by summer-autumn values in the middle of the layer and then followed by late-autumn values at the top. Using the whole seasonal time frame of this gradual change in the season of harvest throughout the layer, I estimated an occupation time of 7 months. This time frame is compared to the estimated amount of meat based on the layer volume.

Layer 8 is represented as a 10 cm thick section of a somewhat circular layer. The assumption of a circular shape is based on the general circular shape of the mound and the overall stratigraphic sequence. This would mean that layer 8 had a radius of 1.4 m and a volume of 0.63 m^3. The volume is based on the area that the layer covers and the general thickness of 10 cm. After the field observations by Williams (2011), this is equivalent to 628 kg of empty shell weight, producing a total weight of ~188.5 kg for shell meat in layer 8. This total amount, divided by the estimate of 210 days (7 months) of occupation time (Fig. 7.6.4), would result in 0.9 kg of procured shell meat per day (Table 8.3).

Volume=		0.6 m^3
	1000 kg per m^3	
Weight-shell		628 kg
	x 0.3	
Weight-meat		188.5 kg
Occupation time		7 months
		210 days
Meat per day		0.9 kg

Table 8.3 Estimations for daily procured shell meat during the accumulation period of layer 8 in JW1727.

This would fall neatly between the two diets based on the observations of Meehan (1977), but only if there was one person using the site. The estimated amount of 0.9 kg /day is far from being definite but by comparison with the observed data, it is in the region of the believable. Table 8.4 compares the previous results of available shellfish meat with the estimated amount of exploited shellfish meat during the occupation period represented by layer 8.

The resulting amount of 0.9 kg of meat per day is only based on the seasonality data proposing 7 months of occupation. However, the seasonality data is only an estimate and the season of some shells can be less precise than others (see chapter 7.4.2). This is why I also included the maximum period (9 months) and minimum period (3 months) of occupation of layer 8. Also the seasonality data is not precise enough to tell whether the shells were continuously accumulated every day or more episodically with gaps of days or weeks between successive episodes of deposition.

JW1727	**Meat per day**	**Occupation period**		**Days per year (1 person) for:**		**Days per year (5 people) for:**		**Days per year (10 people) for:**	
		Days	Yea	16 yrs	82 yrs	16 yrs	82 yrs	16 yrs	82 yrs
Shellfish	2.4	20,375	56	1,273	248	255	50	127	25
Mixed	0.6	81,500	223	5,094	994	1,019	199	509	99
Layer 8	0.9	54,333	149	3,396	663	679	133	340	66
9 months	0.7	69,857	191	4,366	852	873	170	437	85
3 months	2.1	23,286	64	1,455	284	291	57	146	28
Total meat	48,900								

Table 8.4, Duration of site occupation based on amount of shellfish meat at site including proposed durations of layer 8.

The exploitation rates are all within the already observed range of gathered shell meat per day, which is why the overall interpretation of JW1727 is that it is a place of very intense exploitation. Even groups of 10 people could have eaten large amounts of shellfish a few times a week or for a certain period of the year. In this context, it is worth noting that the seasonality data showed an increase of shellfish gathering during summer and autumn, which might be influenced by the increased aridity and lack of other resources (Deith 1988). Following this, the 25 days availability of meat for groups of 10 people on a meat based diet (2.4 kg) or eating for short periods (2.1 kg) could be enough, if they only use it as a seasonal substitute. Of course these are extreme values but the seasonal emphasis of shellfish exploitation needs to be applied to every diet's and group's number of days, because it is clear that there is a seasonal change in subsistence and that the shell mounds do not represent the only food source available.

In retrospect, the comparatively small amount of days each year that JE0004 and KM1057 (and the mounds that their data was extrapolated to by Williams (2011)) can sustain groups of 1, 5 and 10 people for, is not as small anymore. The seasonality data indicates that large amounts of shellfish were only eaten for some part of the year.

If the same emphasis on summer and autumn exploitation is being applied, the measure of sustainability should not actually be days per year but days per shellfish season, which is about 6 months. This virtually halves the time that the shell mounds needed to be used to be part of a subsistence strategy of a local population, making it more possible that they were used every year over a long period.

8.4.5 Comparison of seasonal accumulation rate with radiocarbon dates

After having established a daily accumulation rate for JW1727 based on seasonality data, it is now possible to see how the daily rate compares to the rates based on radiocarbon dates (Table 8.5). The estimations for volume and weight for each midden are based on meat weight data that was presented by Williams (2011). The reason for this is that no actual volume for KM1057 was mentioned and the actual meat weight was already the centre of the other analyses (Table 8.1). Using meat weight as a measure again makes it more comparable here.

Site and proxy	Age min	Age max	Size in m^3	Meat in kg	Shell in kg	Max kg/yr	Min kg/yr	Max m^3/yr	Min m^3/yr
^{14}C									
JE0004	328	511	188	62,700	438,900	191	123	0.6	0.4
KM1057	382	382	785	264,573	1,852,014		693		2.1
JW1727	15	79	163	48,900	163,000	3260	619	10.9	2.1
Seasonality									
JW1727	0.25	0.75	0.63	186	628	754	251	2.5	0.8

Table 8.5 Estimated accumulation rates per year in volume and weight based on radiocarbon dates for JE0004, KM1057 and JW1727 as well as based on seasonality data for JW1727

Table 8.5, estimations for accumulation rates for JE0004, KM 1057 and JW1727 based on radiocarbon dates and also accumulation rates based on seasonality data for layer 8 in JW1727. Note that the maximum accumulation rate is based on the minimum age and vice versa.

Calculating the individual accumulation rates for all sites based on radiocarbon dates and for JW1727 based on the seasonality data, interesting aspects become visible. First of all, the accumulation rate of KM1057 (693 kg/year or 2.1m^3/year) is multiple times that of JE0004 (123-191 kg/year or 0.4-0.6 m^3/year). Their accumulation periods are similar (382 years and min. 328 years, respectively), making it obvious that the accumulation processes at KM1057 must have either been much quicker or more consistently and without gaps. This will also partially be caused by the possibly overestimated size of KM1057, but not completely. When comparing the accumulation rate to the one of JW1727 (min. 619 kg/year or min. 2.1 m^3/year), it is clear that fast deposition is not only found in very big sites, but also in sites that are of similar size as JE0004. Also, looking at the necessary accumulation for JW1727 (3,260 kg/year or 10.9 m^3/year) for a possible age of 16 years (65% probability), it is obvious that even faster accumulations could have been in the realm of the possible. Based on the seasonality data of shells in layer 8, which showed a gradual change in harvesting season throughout the layer, an additional accumulation rate was calculated for JW1727 with 0.8 - 2.5 m^3/year and 251 - 754 kg/year (Table 8.5). This rate fits well with the radiocarbon-based rates in JE0004 (693 kg/year or 2.1m^3/year) and KM1057 (693 kg/year or 2.1m^3/year) as well as the minimum accumulation rate of JW1727 (619 kg/year or 2.1 m^3/year).

To use this rate and see how it would work for the other sites, I made basic estimations of how many years it would take to accumulate the various shell mounds with the accumulation rate found in layer 8 (Table 8.6, Fig. 8.19).

			Years until full volume		**Years until full weight**		**Years of age based on ^{14}C dates**	
Site	Size in m^3	Meat in kg	2.5 m^3/ yr	0.8 m^3/yr	754 kg/yr	251 kg/ yr	Age min	Age max
JE0004	188	62,700	78	235	83	250	328	511
KM105	785	264,573	327	981	351	1054	382	
JW1727	163	48,900	68	204	65	195	16	82

Table 8.6, years until 'completion' for each shell mound using the minimum and maximum accumulation rates from layer 8 in JW1727 compared to the years of age based on radiocarbon dates.

For the two sites that were previously analysed by Williams (2011) the difference between the ages based on the radiocarbon dates and the ‘realistic’ estimated ages based on the rapid accumulation from layer 8 is evident but difficult to interpret. For JE0004, the new estimated years of accumulation (~80 - ~240) are far below what the radiocarbon dates suggest. This can either be explained with unknown hiatuses in occupation or smaller accumulation rates than the ones in layer 8 of JW1727. The two different phases in JE0004 indicated by a change in species composition would suggest some degree of interruption. The new estimates for the ‘realistic’ accumulation period agree with this.

For both sites, KM1057 and JW1727, the ‘realistic’ accumulation period falls closer to that which was suggested by radiocarbon dates (KM1057, min:~340 years, max: ~1000 years, radiocarbon: ~382 years. JW1727, min: ~66 years, max: ~200 years, radiocarbon: 16-82 years). Even more interesting, the more rapid accumulation rate of 2.5 m^3 or 754 kg per year, which is based on the extremely short (3 month) occupation period of layer 8, produces an estimate that is closer to the radiocarbon date than the assumed time period (7 months) or the maximum time period (9 months) are.

Following only the assumed time period, it would be more likely that the JW1727 accumulated within a time period that is closer to the proposed age of 82 years (probability: 95%) than 16 years (65% probability). Any age that was below 65 years would need to have an accumulation rate that exceeds what is possible giving the assumed seasonality data in layer 8 (7 months).

It is a possibility that the other layers in JW1727 accumulated much quicker than layer 8 but do not show a quicker accumulation in the seasonality data. It is equally possible that a sequential change in seasons, as was evident in layer 8, is not a necessary characteristic of rapidly accumulating layers, because other rapidly accumulated layers have simply been deposited differently.

Previously (Chapter 7.5) I argued that it is possible in certain taphonomic situations, that rapid accumulations like layer 8 do not necessarily show up as a singular season or a gradual change. This is likely because they are not sampled according to their seasonal sequence (a rarity and likely an opportunistic stab in the dark). Reflecting on this and including the radiocarbon dates, it is obvious that the alignment of seasonal and stratigraphic sequences is not the typically recorded archaeological context but the result of a very typical process happening at JW1727 and possibly also at KM1057..

My hypothesis is that most layers of JW1727 might well have accumulated faster or as fast as layer 8. Just because their seasonal signals are not in stratigraphic order does not mean they were not rapidly accumulated.

8.4.6 Summary

In summary, the availability of meat from previous analyses (Williams 2011) is much lower than what new estimates suggest. Also, there was a striking similarity in the dietary models of ethnological data and specific parts of JW1727 (i.e. layer 8). Seasonality data from layer 8 was used to estimate a daily meat availability of 0.9 kg/day, which lies within the applied diet models used by Williams (0.6 kg/day and 2.4kg/day, see Meehan 1977) but would only be enough for every day if there are one or two people using the site throughout the year. Calculations led to similar amounts of days per year at which shellfish was eaten.

All three sites were unable to supply shellfish meat for every day of the year if more than 5 people were using the site. However, the seasonality data from JW1727 (Chapter 7), which showed an emphasis in summer and autumn, showed that there clearly are other food sources being eaten more or less intensively in other seasons and these are now missing in the record.

The accumulation rate of layer 8 based on seasonality data was also compared to the estimated longevity of JW1727 based on radiocarbon dates. It showed that the estimated time frame of accumulation between 16 years (65% probability) to 82 years (95% probability) was only in accordance with the most rapid accumulation rate that was theoretically possible in layer 8 (2.1 kg/day), and that a time frame of below 65 years is less than probable if the assumed rate (0.9 kg/day) was applied. Because the seasonality data is conclusive and the assumed rate for layer 8 very likely, I concluded that layer 8 is not the most rapidly accumulated deposit in JW1727 but was only disturbed less than other layers and was also sampled in a fortunate location.

One big unknown aspect are the activities that led to the deposition of the different layers in JW1727. The taphonomic preconditions that lead to the alignment of stratigraphic and seasonal succession to make it possible to estimate accumulation rates need further analysis and a detailed framework of the archaeological context.

8.5 Summary of sustainability evaluation

With this chapter I tried to address the questions about how sustainable and how attractive coastal life on Farasan could have been. The site compositions from three sites were analysed for signs of resource depression and the calculations made by

Williams (2011) about meat availability and possible group sizes were supplemented with new information about meat-weight and temporal information on higher resolution. How has this new data and the additional proxies changed what we know about shell accumulation on Farasan?

1. The comparison of species composition between the sites showed that marine resources were rich enough for a sustainable pattern of coastal exploitation. The dominant species *C. fasciatus* showed no signs of anthropogenic resource depression. Furthermore, the size distribution of *C. fasciatus* shells change between different locations indicating that differences in the marine environment related to factors such as geomorphology are the main factor of influence.
2. Shell meat estimates and occupation periods from JW1727 and KM1057 demonstrate that small groups of 2-3 people could have lived on a mixed diet for the whole occupation time and groups of 5 could have lived on a seasonal shellfish diet with the meat available. JE0004 is too small a site to support a small group for its whole occupation time.
3. Accumulation rates based on radiocarbon dates and seasonality data correspond well for KM1057 and JW1727. They indicate rapid accumulation with over 2 kg of shell meat per day. The rates based on radiocarbon dates also leave the possibility of even faster accumulation and more intense exploitation than what was suggested to be a 'realistic' rate based on seasonality data in layer 8. This divide suggests that layer 8 of JW1727 is not actually the most rapidly accumulated deposit in the shellmound. A similarly intense exploitation can be assumed for KM1057, which although it lacks the seasonality data, produced results for average shell size and proportion of *C.*

fasciatus that indicate rich marine environments. JE0004 has a very long occupation period for its size and accumulation rates in comparison to 'realistic' amounts of shell collection indicate one or more occupation hiatuses.

4. It is apparent that extensive shallow water areas are important for large scale exploitation of *C. fasciatus*. Both, KM1057 and JW1727, had larger specimens and higher percentages in species composition. This suggests that the exploitation intensity represented by them is more likely to be applicable for other shell mounds, than the lower intensity represented by JE0004. Whether the accumulation of JE0004 was part of an equally productive exploitation pattern that simply focused on resources other than *C. fasciatus*, needs to be considered and is a possibility. Especially the occurrence of fish bone pockets is an indicator for this.

Chapter Nine

Coastal landscape of Arid Arabia

9.1 Introduction

In this chapter I discuss how the results of the seasonality chapter could help to understand the wider archaeological context of the Farasan shell mounds. In previous studies it was argued that the change to an arid climate was a possible cause for the start of intensive exploitation of coastal resources on Farasan (Williams 2011) and also in other parts of the Arabian Peninsula (Preston et al. 2012). To analyse this possible response to aridification on Farasan, I investigate the isotopic differences between archaeological shells of different periods and discuss what these differences can mean for the aridity of the environments in those periods. Also the general mobility of the population is discussed and how much of a role coastal exploitation played.

The chapter firstly provides environmental data based on $\delta^{18}O$ and $\delta^{13}C$ values from different periods of occupation on Farasan (**Chapter 9.2**). It then discusses the archaeological information from this study with the outcomes from both sides of the Red Sea and from similar archaeological sites on the southern coast of Arabia (**Chapter 9.3**) to come to a general conclusion about coastal subsistence during the Arabian Neolithic.

9.2 Environmental study

9.2.1 Introduction

This section discusses the possible impact of environmental change on the emergence of coastal exploitation of Farasan in particular and the southern Red Sea in general. As has been described before (Chapter 2), the Farasan shellmounds accumulated over a period from 6,500 to around 4,500 cal BP (Bailey et al. 2013). This time frame of exploitation is on the fringes of a climatic change from a humid to a more arid climate between 8,000 and 6,000 cal BP, covering the North of Africa, Arabia and parts of India (Adamson et al. 1980, Arz et al. 2003, Van Campo et al. 1982, Rossignol-Strick 1983, 1985, Pachur and Kröpelin 1987, Hoelzmann et al. 1998, Bar-Matthews et al. 1999, Gasse 2000, Fleitmann et al. 2007).

The analysed periods are represented by the two shell mounds JW1727 and JE0087, dating to 4,800 cal BP and 6,500 cal BP, respectively. Comparing the stable $\delta^{18}O$ and $\delta^{13}C$ isotope values of shell carbonate from those periods with each other can indicate changes in the environment like changing humidity, evaporation or sea surface temperature.

The chapter begins with an overview of the climatic proxies in the mid-Holocene, which build up the climatic framework for this study. This is followed by a brief description of the analysed shellmounds and the sampled layers. After this, the stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes from archaeological shells are compared to each other and also to the modern data (Chapter 6), followed by their discussion and general conclusion.

The humid conditions in the early Holocene are associated with a northward displacement of the summer monsoon due to a shift in the intertropical convergence zone (ITCZ) to 23ºN (Biton et al. 2010). The influence can be seen in the large number of environmental records available from wetlands and lakes from all of Arabia (Fig. 9.1, (Lezine et al. 2014)). From this climate optimum onward to 5.000 cal BP, a climatic deterioration can be found that had an impact on lacustrine records and records from spring deposits. The marine records of aeolian dust transported from arid areas and deposited in the Arabian Sea (KL74, Sirocko et al. 1993) also show a distinct increase of sand deposition around 7,000 cal BP after a 3,000 year period of an almost complete pause. Van Rampelbergh et al. (2013) compared different proxies from the southern Arabian Peninsula and found a gradual change towards arid landscapes at around 7,000 cal BP for the Yemeni lowlands and for the Yemeni highlands at 5,000 cal BP. Isotope records of planktonic foraminifera *Globigerinoides ruber* from the northern and the central Red Sea show an abrupt change in $\delta^{18}O$ from 7,000 to 6,500 cal BP (Arz et al. 2003).

Exactly when this increase in desertification was noticeable on the coastline of the Arabian Peninsula and on Farasan in particular, is not clear. But it is possible that the exploitation of coastal resources that happened on Farasan at the beginning of the arid period is a response to the vanishing of other food sources all over Western Arabia. Chapter 3 introduced some of the theories behind the marginalisation of coastal resources and shell middens in particular. A population movement away from formerly fertile inland areas and towards the less favourable sea would fit well into the extreme interpretation of coastal landscapes as "Gates of Hell" (Erlandson 1994). But it is not clear how the climatic situation on the Tihamah lowlands near Farasan compares to the Yemeni dataset from sites more inland (van Rampelbergh et al. 2013). Similarly, it is not clear if it would have caused people to migrate all the way to the Farasan Islands. However, it is possible to get some estimate of how the environment changed on Farasan itself and see if it had an influence on how people generally exploited the marine resources all over the southern Red Sea.

9.2.2 Spatial and temporal context of the sites

Shellmounds JW1727 and JE0087 are both located at Janaba Bay on Farasan Kabir (Fig. 9.2). While JW1727 was radiocarbon dated to 4,800 cal BP the shellmound JE0087 was radiocarbon dated to 6,500-6,000 cal BP (Fig. 9.3, Table 9.1). From the base of the midden to the top, four radiocarbon dates were taken that indicate two separate occupation periods, a very short one around 6,000 cal BP and an early one of unknown length at 6,500 cal BP (Fig. 9.3, green).

Site	**Lab no.**	**Layer**	**^{14}C-Age**	**Mar. Res. Corr.**	**BP Range 2σ**	**Material**	**Species**
JE0087	OxA 28,386	14	5132 ±31	-	5927-5769	charcoal	unidentified
	OxA 28,072	14	5718 ±30	-100 ±50	6093-5934	shell	*C. fasciatus*
	OxA 28,413	27	5232 ±29	-	5995-5935	charcoal	unidentified
	OxA 28,618	35	6185 ±31	-100 ±50	6580-6431	shell	*C. fasciatus*
JW1727	OxA 28,009	2	4851 ±31	-100 ±50	5108-4873	shell	Mussel (*Brachidontes* sp.)
	OxA 27,890	17	4202 ±29	-	4835-4660	charcoal	unidentified
	OxA 27,889	23	4287 ±29	-	4861-4838	charcoal	unidentified

Table 9.1: Radiocarbon dates from JE0087 and JW1727

Unlike other shellmounds the JE0087 shellmound is not part of a group of sites located on a long palaeo-shoreline, but located behind it on a separate beach ridge further inland (Fig. 9.4). It is over 2 m in height and has a diameter of 25 m (Fig. 9.5). During the excavations in February 2013, a 10 m long section from the rim to the centre was excavated and bulk samples were taken in a column at the inside end of the trench. The analysed column showed a distinct sandy layer with mixed in *C.*

fasciatus shells, indicating flooding events and reworking of the top layers of the midden during a period of abandonment (Fig. 9.6). No traces of soil formation processes were found. The overall stratigraphy is made of layers with whole *C. fasciatus* shells alternating with thinner layers of fish bones and fragmented shells. There is also a larger proportion of *Chicoreus* sp. shells, which sometimes occur as distinct layers. Evidence of hearths and extensive ash layers were found, and a few lithics made of local limestone.

The analysed shells from JE0087 (n=3) are from layers 36 and 37. Layer 36 is almost exclusively *C. fasciatus*–supported and well preserved. Layer 37 is located below this *C. fasciatus* layer and is mostly made of sand with some shells mixed into it. Layer 36 and layer 37 are both covered by a hearth feature (Layer 35) and together represent the older part of the midden at 6,500 cal BP (Table 8.4.1). Sequential carbonate samples were drilled from the shell edge to the protoconch, according to the sampling method of juvenile *C. fasciatus* shells (Chapter 5). The range of the values was compared to the overall range of stable isotope values from all shells in JW1727 and the range of all modern shells in the dataset.

9.2.3 Results

Similar to modern specimens (Chapter 6) and shells from JW1727 (Chapter 7) the shells from JE0087 reflect a range fitting seasonal variations in SST (Fig. 9.7). Comparing the total $\delta^{18}O_S$ ranges of all carbonate samples (Fig. 9.8), shells from 4,800 cal BP (n = 59) exhibit values ranging from –0.2‰ to –2.2‰ ($\Delta^{18}O_S$ = 2‰), shells from 6,500 cal BP (n = 3) show values ranging from –0.1‰ to –1.9‰ ($\Delta^{18}O_S$ = 1.8‰) and modern shells from –0.3‰ to –2.8‰ ($\Delta^{18}O_S$ = 2.5‰). All ranges are fairly similar. Only the modern values have a slightly wider range and a slightly lower average (modern: –1.4‰; 4.8kyr cal BP: –1.18‰; 6.5kyr cal BP, –1.13‰).

By contrast, average $\delta^{13}C_S$ values in archaeological specimens are invariably higher compared to modern counterparts. The modern average lies at +1.3‰, while values from archaeological shells from 4.8 kyr cal BP are at +3.5‰, from 6.5 kyr cal BP at +3.2. More specifically, archaeological shells exhibit $\delta^{13}C_S$ values ranging from +1.5‰ to +5.3‰ ($\Delta^{13}C_S$ = 3.8‰) and +1.5‰ to +6‰ ($\Delta^{13}C_S$ = 4.5‰), respectively. This is much higher than the modern range of $\delta^{13}C_S$ from +0.2 to‰ +2.9‰ ($\Delta^{13}C_S$ = 2.7). In general no correlation between $\delta^{18}O_S$ and $\delta^{13}C_S$ was observed for archaeological shells.

9.2.4 Discussion

The average sequential $\delta^{18}O_S$ values of specimens from 4,800 (JW1727) to 6,500 cal BP (JE0087) are comparable to those recorded by modern specimens. Modern shells, however, exhibit a larger seasonal amplitude ($\Delta^{18}O_S$ = 2.5‰) compared to archaeological counterparts ($\Delta^{18}O_S$ up to 2.0‰). This difference might imply a higher seasonal contrast, with warmer summers today compared to the time of the shellmound formation.

Other marine records of the Red Sea during the Holocene suggest a decline in relative humidity connected to the southward displacement of the ITCZ between 7,000 and 6,000 cal BP (Fleitmann et al. 2007). Accordingly, Arz et al. (2003) found an increase of $\delta^{18}O$ values from –1.0‰ to –0.6‰ in the Gulf of Aqaba and from –1.4‰ to –0.6‰ outside the Gulf of Aqaba in the North of the Red Sea, by measuring planktonic foraminifera (*Globigerinoides ruber*) from sediment cores. But on Farasan the average values for $\delta^{18}O_S$ change insignificantly between 6.5 kyr cal BP (–1.13‰) and 4.8 kyr cal BP (–1.18‰). Even more confusing, the average $\delta^{18}O_S$ decreases by 0.3‰ between the mid-Holocene and now, indicating an increase in humidity. How comparable the $\delta^{18}O$ values of the marine shells and the foraminifera are, is not entirely clear. The possible dependence of $\delta^{18}O$ in *C. fasciatus* shells on the local environment has been mentioned before (Chapter 5) and could also be an important factor when comparing more general proxies like foraminifera to more specific ones like local marine shells. Additionally, more recent developments in SST (Raitsos et al. 2013) have shown that the Farasan Islands are in an area where temperatures have increased dramatically in 1994 (+0.8ºC when comparing two time frames of 1985-1993 and 1994-2007). An increase of +0.8ºC would decrease the $\delta^{18}O$ values by ~0.2 ‰ and it could explain the low values found in contemporary shells.

The $\delta^{13}C_S$ values notably differ between archaeological and modern samples. The modern shells display a much lower seasonal $\delta^{13}C_S$ variability ($\Delta^{13}C_S$ = +2.7‰) than the archaeological specimens from JW1727 ($\Delta^{13}C_S$=+3.9‰) and JE087 ($\Delta^{13}C_S$=+4.5). Additionally, the averages of $\delta^{13}C_S$ have decreased from 6.8 kyr cal BP ($\delta^{13}C_S$=+3.17) and 4.8 kyr cal BP ($\delta^{13}C_S$=+3.53) to modern times ($\delta^{13}C_S$=+1.28). The reasons for this are difficult to explain. A general $\delta^{13}C$ increase of 1-1.5‰ can be expected for carbonate records that predate the industrial revolution and the accompanying increase of ^{12}C in the atmosphere due to the burning of fossil fuels (Friedli et al. 1986, Surge et al. 2003). In marine records this effect is more moderate due to mixing of surface and deeper (older) waters (Cage and Austin 2010), but between 1970 and 1990 the mean global surface ocean $\delta^{13}C$ still increased by 0.16±0.02‰ (Quay et al. 2003). Consequently, the oceanic Suess effect could largely explain the majority of the ^{13}C-enrichment of the shell.

An alternative, or additional explanation, could be an overall increase in $\delta^{13}C_{DIC}$ in the southern Red Sea. ^{13}C-enrichment in seawater DIC pool is often interpreted as the product of an increased nutrient and rate of photosynthetic activity in surface water (McConnaughey 2003). Today, the summer monsoon is responsible for lateral advection of nutrient-rich water from the northern Arabian Sea into the Red Sea. The injection of upwelled water from the Gulf of Aden controls the vertical nutrient recycling and increase in primary productivity in this region (Bouilloux et al., 2013). This injection of nutrient rich water due to monsoonal activity from the Arabian Sea into the southern Red Sea might have continued for much longer than other records indicated (Fleitmann et al. 2007, van Rampelbergh et al. 2013). Even though the ITCZ had moved too far south to sustain a humid environment in Arabia, it was still causing the upwelling effect in the Arabian Sea and impacting the southern Red Sea through this injection. This would have gradually decreased as well but be delayed by some degree.

9.2.5 Summary

To sum up, the differences between the archaeological shells were not as great as the differences between archaeological and modern shells. For the marine environment that is associated with the shell mounds, this means several things:

1. The $\delta^{18}O_S$ and $\delta^{13}C_S$ ratios of the eastern and the western parts of Janaba Bay are not too dissimilar.
2. The changes in $\delta^{18}O_S$ and $\delta^{13}C_S$ ratios in shells from Janaba Bay between 6,500 cal BP and 4,800 cal BP are not significant.

3. The changes in $\delta^{18}O_S$ ratios between archaeological and modern shells demonstrate an increased seasonal amplitude with hotter summers for modern shells.
4. The changes in $\delta^{13}C_S$ ratios between archaeological and modern shells are showing a possibly less intense primary production.

Comparing the shell carbonate from the two archaeological periods did not show changes, implying that the amount of precipitation and the overall aridity of the environment was in fact the same. Also there is no indication of a less rich marine environment. It must have been highly productive throughout the Holocene, and evidently it still is. Based on the stable isotope data, I argue that there has been no dramatic environmental change between the small-scale exploitation that is represented in the first layers of JE0087 and the big-scale exploitation represented by JW1727. The gradual change to an arid environment over several thousand years that was found in some studies (Fleitmann 2007, van Rampelbergh et al. 2013) was not as evident as the abrupt change around 7,000 cal BP that was found in others (Arz et al. 2003, Sirocko et al. 1993). Following this it is more likely that the Tihama lowlands and also Farasan became arid much earlier and more rapidly than the highlands.

The earliest radiocarbon dates that are available show small scale shell gathering activities in an already arid landscape. For the site JE0087, its first remains of exploitation activities got subsequently buried by sand and eventually the site was reused as a more intense shell deposition site. The radiocarbon dates indicate that there are several hundred years between those two phases and that different people were reusing JE0087. By that time the site was possibly only an indicator for the presence of shellfish in the nearby water and had no relation to the people that previously used JE0087. This leaves us with several questions.

How did people get from these short instances of shell gathering to the intensive use of shellfish? What happened during the time of abandonment of JE0087? Connected to this, what happened between the occupation of JE0087 and the sites that are located in front of it? What happened on the mainland at the same time?

9.3 Coastal landscape of arid Arabia

9.3.1 Introduction

The above section already opened up some questions about how aridity influences the subsistence of people on Farasan and southern Arabia in general. In previous chapters I mention theories about how aridity is linked to high mobility and how a mostly marine subsistence also depends on terrestrial food sources (Chapter 3). In the following I discuss these theories with the results of the seasonality study (Chapter 7) and my estimations of the sustainability of coastal exploitation (Chapter 8). The data presented there fits into the wider discussion about mobility and subsistence in mid-Holocene Arabia as most of the developed theories can be boiled down to the question of how sustainable the coastal landscape was, after the monsoonal shift towards the south that caused the lack of summer rains and aridification of the landscape (Cremaschi et al. 2015).

The section firstly describes theories about mobility and coastal exploitation in Eastern Arabia (**Chapter 9.3.2**). The theories developed there are then applied to the Farasan Islands and the wider region of the Tihamah coastline (**Chapter 9.3.3**). The section concludes with a discussion of preservation and unknown factors of coastal life on Farasan (**Chapter 9.3.4**).

9.3.2 A concept of high mobility and low coastal subsistence in East Arabia

Despite the distance between them, the environmental setting and general aridity since the mid-Holocene put similar constraints onto subsistence strategies on sites in East Arabia and sites in the Tihamah. Several different theories have been proposed, for how people coped with the more arid climate and how they lived in coastal areas in comparison to the more humid mountainous places (Biagi and Nisbet 2006, Cavulli and Scaruffi 2013, Uerpmann et al. 2000, Zazzo et al. 2014).

Detailed research has been undertaken in the United Arab Emirates (UAE) and Oman (Berger et al. 2013, Biagi 1987, 1994, Biagi et al. 1984, Biagi and Nisbet 1999, 2006, Uerpmann and Uerpmann 1996, 2000, 2003, Uerpmann et al. 2010, Uerpmann 2003,). The UAE site of al-Buhais dates to 7,200 cal BP to 6,200 cal BP and includes a major graveyard with over 250 individuals as well as midden deposits that contained a large amount of artefacts and faunal material (Uerpmann et al. 2000). No structures were found but extensive distribution of fire-pits and the repeated use of them makes this site longer lasting than the lack of structures suggests. The faunal assemblage at al-Buhais contains mostly domestic animals: cattle (*Bos taurus*), sheep (*Ovis aries*) and goat (*Capra hircus*), but also wild animal:, Arabian Oryx (*Oryx leucoryx*), gazelle (*Gazella gazella*), Camel (*Camelus* sp.), wild ass (*Equus africanus*) and wild goat (*Capra aegagrus*) or ibex (*Capra nubiana*). Domestic animals dominate the assemblage with 90% of the total weight. Clearly the focus of these people was not simply hunting the local animals but herding domesticates. Uerpmann et al. also emphasise that the age distribution of the domesticates do not accurately represent the actual age distribution of the herd as there are many younger animals missing. They use this as an indicator against a long-term occupation and together with the lack of structures interpret the human population as mostly mobile. This is attributed by the fact that most burials are secondary burials and people are unlikely to have died close to the graveyard. Additionally, the reconstruction of their diet indicates large contributions of marine food sources. Interestingly, contemporary coastal sites show little use of mammal bones and are predominantly composed of shellfish remains (Uerpmann and Uerpmann 1996). A seasonal cycle has been proposed that includes herding animals in the higher mountains with low summer temperatures, collecting shellfish in the winter time and making use of pastures in the lower uplands of al-Buhais in spring. This would also include the site at Jebel Faya (FAY-NE15) a contemporaneous graveyard with a similar composition to al-Buhais but some differences that could indicate that different groups inhabited each site (Kutterer and De Beauclair 2008).

Cavulli and Scaruffi (2013) align their main model of mobility for coastal population in Oman after the seasonal model found for the UAE. Their estimations of the overall mobility is mainly depending on the sustainability of the coastal landscape in the Ja'lãn region, Oman (Fig. 9.9). Between the extremes of a high mobility connected to a scarce landscape (Theory 1) and sedentarism connected to a rich landscape (Theory 2) they find that a model with micro-regional mobility fits the archaeological record the best (Theory 3). This micro-regional model is closely related to the seasonal model by Uerpmann et al. (2000).

Long distance travelling or macro-area nomadism (Theory 1) is generally thought to play a big role in desert landscapes because of the scarcity of food (Veth 2005, Smith 2005). The high mobility would allow people to herd in the mountains or oases far inland, of which some remains in the UAE have been found (Uerpmann 2003), alas not yet in Oman. Of course an extremely mobile population that moves through the South Arabian Peninsula would cause less impact on the landscape and with less impact also a lack of archaeological sites. But a highly mobile population should also be represented by a very similar material culture of sites from different regions, which is not the case (Cavulli and Scaruffi 2013).

A completely sedentary population (Theory 2) is similarly difficult to find. Modern ethnological data from the Ja'lãn region suggests that the coastal resources were not abundant enough to supply people with fish for longer periods during the mid-Holocene (Lancaster and Lancaster 2002). Following the 'Gates of Hell' approach (Erlandson 1994, p. 273), the less productive coastal activities needed to be supplemented with the use of the highland landscapes that had abundant fresh water and better pastures for herding. This is attributed by the faunal remains of herding animals indicating a subsistence strategy that herding animals are an important part of (Uerpmann et al. 2000). Also, some degree of mobility is represented by the remains of fragile structures in the Ja'lãn region. The structures that were found at coastal sites like Ra's al-Khabbah KHB-1 would not have provided enough protection from the strong winds in the summer (Cavulli and Scaruffi 2013), which makes it less likely that the structures were meant to be stationary.

The above suggests that life at the coast was neither sustainable nor preferable to living in the more temperate and fruitful mountain area. Nevertheless, archaeological sites are predominantly found in the coastal regions (Berger et al. 2013) and show signs of long-term occupation as well as a material culture that implies a more sedentary nature (Biagi and Nisbet 2006). Coastal sites (RH-3, RH-4, RH-5) with more or less constant occupation were found in Oman with evidence for shellfish exploitation and also for the use of herding animals (cattle, goat and sheep) (Biagi 1987, 1994, Biagi et al. 1994). The sites are part of a bigger cluster of sites that are closely related to Qurum, a mangrove swamp. Radiocarbon dates put the sites into a period from 6,500 cal BP to 4,500 cal BP although other sites in the same region also produced dates as old as 8,000 cal BP.

To explain this, Cavulli and Scaruffi propose a seasonal movement between the coastal sites and the mountainous regions 20-30 km inland to supplement the marine diet by moving into the uplands in times of low marine productivity (Theory 3). A faunal analysis of the ichthyofauna of the gulf coast suggested that fish are only available seasonally and that they migrate away from the shore. This would make it necessary for people to carry out off-shore fishing in larger boats. Remains of those were not found at the archaeological sites, although an analysis by Beech (2004) showed that there is evidence of off-shore fishing in the form of tuna/mackerel remains.

The faunal remains (cattle, sheep, goat) also fit to a seasonally mobile population that moves to and from the coastline every year (Uerpmann et al. 2000). Herding animals would make it necessary to collect enough terrestrial food for them throughout the year, which makes it likely that people moved into the uplands when the lowlands became too dry in the summer.

For the upland areas in Ja'lãn no sites have been found as of yet, which could partially be due to the small impact that herders had on the landscape, because of their fairly mobile nature. The UAE sites of al-Buhais and also the site Jebel Faya (Kutterer and De Beauclair 2008) show evidence of highland herding but this could be explained with a different kind of centrality of those sites in comparison to their coastal equivalents. In the Ja'lãn region, upland sites are argued to be more ephemeral and only be used, when temperatures in the lowlands were too high and fish were widely unavailable.

Conversely, the chances of people to migrate to the mountains, even only seasonally, have recently become very small with the evidence for a predominantly marine diet found in the individuals of RH-5 (Zazzo et al. 2014). Zazzo et al. made use of bioapatite in human bones and of tooth enamel to evaluate the dietary components of the individuals. Bioapatite was the solution to the lack of preserved bone collagen, which is a common characteristic in burials in arid and hot regions (see also Zazzo 2014 and Maurer et al. 2014). Equally problematic are the local marine and terrestrial foodstuffs, which overlap in stable carbon and stable nitrogen isotope values. This problem was solved by using the radiocarbon (^{14}C) values and the marine reservoir effect as an indicator. Generally radiocarbon dates from marine samples will be 400 years older than their terrestrial counterparts because marine carbon is in a different equilibrium to the atmospheric carbon, which is called the marine reservoir effect (see also Cook et al. 2015). This effect is inherent to radiocarbon values of marine organisms and can also be found in the radiocarbon values of a human whose subsistence is based on marine food. Analysing the radiocarbon values of human individuals in comparison to terrestrial samples (i.e. charcoal or terrestrial fauna) can give insight into how much the individual's diet was dominated by marine organisms as it produces an older radiocarbon date than the terrestrial counterpart. The analysed samples at RH-5 are from human remains, charcoal and shell. Each sample material was taken from 8 different graves to secure similar dates of deposition. For all 8 individuals the results indicated a predominantly marine diet. This means that inland movement could have been possible to a small degree, but the results do not suggest it to be a major part of any individual's life or happening on a seasonal basis.

This changes the understanding of mobility and sustainability of coastal sites in arid environments as it rules out a regular movement to inland pastures over longer periods. More importantly, it marks that people have lived on a marine diet without the need to complement the coastal resources in hotter parts of the year.

At least for the coastal sites in the Ra's al Hamra the movement to and from the coast and a seasonal use of the mountains is not likely and evidently not necessary, although mobility along the coastline is still possible and could have taken place when resources became too scarce.

9.3.3 Applicability of coastal subsistence and mobility concepts

How do the above theories apply to the Red Sea? Following the model of macro-area nomadism (Theory 1), the aridification would have enforced a highly mobile population that seasonally moves from the coast to the uplands. Similar to the coastal hinterland in eastern Arabia, the Tihamah would become a transitional area for mobile herding communities leaving behind little archaeological evidence. Even more, the seasonal movement to the coasts to make use of fishing could have been the main driver for trading. The mountains are rich in lithic resources and the trade with shell ornaments is possible (Tosi and Usai 2003), even though not yet evident in this area. Shell beads were found in sites on Farasan (Eva Laurie, pers. comm.) and are also common in sites in Oman (Cavulli and Scaruffi 2013) as well as on the other side of the Red Sea (Bar-Yosef-Mayer and Beyin 2013). Lithic tools found in the Dhofar region (Oman) are likely to have originated in the Yemeni Yafa mountains according to geochemical analyses (Fig. 9.9) (Khalidi et al. 2010, 2013), which means over 1000 km of transporting network. Also the use of stone tool material originating in Africa was found in the Tihamah (Khalidi 2009, see also Zarins 1990), proving the occurrence of long-distance trade networks across the Red Sea.

It is attractive to use all this to argue for the use of the Tihamah as being a stop between mountains, as an area of transition that is being crossed by traders and herders during certain times of the year.

However, this does not fit with the results of my study and others. First of all, Khalidi et al. (2013) showed that the connections between African lithic sources and the Tihamah sites are much stronger than the connection with the much closer Arabian sources in the Yafa highlands, which does not rule out any connections but makes a strong exchange between uplands and lowlands much less likely. It also strengthens the connection between coastal sites around the Red Sea. Additionally, my study has shown that there is no reason to believe that the marine resources have been depleted because of intense human exploitation (Chapter 8). The seasonality results of my study also showed that the coastal exploitation on Farasan did not happen seasonally but throughout the year (Chapter 7), negating seasonal movement of people as well as marine resources (Theory 3).

Similar to the remains of coastal sites in Oman (Biagi 1987, Biagi and Nisbet 2006) and the site RH-5, which showed some traces of herding and hunting but is generally dominated by marine resources, which is also mirrored by the marine diet of its inhabitants, the shell mounds on Farasan are likely to be the result of people that are fairly sedentary and do not rely on terrestrial fauna or the need to move because of food scarcity.

Following this, is it possible to conclude a population that is only sedentary for Farasan or people at the Tihamah? Should we exclude any migration patterns between the islands and the mainland? Was there some exchange between the islands and the mainland, but not very intensive? The majority of the data from earlier studies found only some evidence that there was intense contact with the mainland

and it was mainly based on the lithic artefacts and the similarity with sites on the other side of the Red Sea (Alsharekh and Bailey 2014, Bailey et al. 2013, Meredith Williams et al 2014b, Williams 2011).

How difficult it was for people to navigate the 40 km of sea to get to the mainland is not clear. Travel between the individual islands of the archipelago must have happened more regularly but these journeys are also much less difficult. Meredith Williams et al. (2014b) argued that the easiest route to the mainland is not the direct route but may be a longer route making use of intermediate islands as stopping points. Island hopping would have been less difficult and the islands in the south of the Farasan Islands build an arch towards the mainland. The longest trip would have been around 10 km, which is not enough to necessarily lose sight of the coastline. Also knowledge of the locations of islands must have been enough to navigate between them.

In this context it is worth mentioning the importance of smaller islands for coastal exploitation and that they can facilitate a lot of migration. In the Caribbean small islands have been shown to be of a higher value than previously thought. There is a bias in the research that is linked to the preconception that larger islands also provide more resources and are thus more important for the long-term development of occupation. Research by Keegan et al. (2008) showed that not only do small islands have a variety of terrestrial resources available but also the amount of marine resources is generally higher. They argue that the association of small islands with the banks and shallow water areas in their vicinity is able to support a variety of marine wildlife, which although less visible is probably equally important as terrestrial food sources. In this regard the actual size of the islands does not matter but rather the amount of possible marine habitats that surrounds the island.

It is possible that an equal opportunity in coastal exploitation was seen in the islands between Farasan and the mainland (Zamhar, Fasht and Buklan). The movements between both could therefore have been much less of a dangerous journey but a productive one as in combination with possible trade. Satellite imagery has revealed possible shell middens on the small islands (Meredith-Williams 2014b). What exactly the connections are between the small islands sites and the mainland sites or the Farasan sites, has not been analysed yet, but they are potentially part of the same subsistence system. Regardless of their actual date, the small island sites are evidence of the richness of marine resources in the area and it is likely that people in the mid-Holocene could have made use of the marine resources at those islands.

The intensity with which this connection was used is difficult to ascertain. As mentioned above, there are only a few lithic artefacts that originated on the mainland and are evidence of contact. Also it is difficult to find more artefacts because the shell mounds have low artefact densities relative to their volume.

That said, we cannot exclude the movement of small groups or single individuals that had strong, maybe even personal, connections to the mainland. Even today it is no problem to eat fruit and meat from far away, simply because a fraction of the population sees it as beneficial to make the trip. Also it is possible that there have been frequent exchanges of people, without the overall population of the islands changing significantly.

Both processes would account for the possible influence of people from the Arabian mainland and also the African mainland. In this context the occurrence of shell mounds of similar number and distribution on the Dahlak islands in Eritrea cannot be ignored (Meredith-Williams et al. 2014b). More similarities can be found in the knapping technique of obsidian artefacts from both regions (Khalidi et al. 2013, Zarins 1990). Also lithic analysis indicates that mostly pre-prepared nodules of obsidian were transported to the Tihamah, so they could be traded with and only after the nodules had reached the Tihamah they had been worked on (Khalidi 2007). Especially in comparison with the distance of each archipelago to its corresponding mainland the distance between the two continents at the Gulf of Aden is very small. The Red Sea does not seem to be a barrier for cultural exchange (Bailey 2007, Meredith-Williams et al. 2014b, see also Lambeck et al. 2011). The opposite is plausible, in connection with the marine productivity of the coastal landscape and the small islands in the Gulf of Aden, the Red Sea enables cultural exchange rather than prevents it.

9.3.4 Unknown factors of coastal life

The above results also showed that there is a lot that is still unknown to us. Cavulli and Scaruffi (2013) argued that the structural remains of coastal sites are not enough to cope with the strong winds and rain for longer periods, but evidently it was possible to live in those conditions. It is possible that the structural remains that were found provided more shelter than previously thought. Also the structures may not have left any traces for archaeologists to find.

The same can be said for the coastal landscape of the Tihamah and for the Farasan Islands shell mounds. Here no structural remains were found and only traces in the form of postholes indicated some degree of habitational structure. For reasons unknown, the Farasan population chose not to use any of the bedrock available to build more permanent structures. Broken off slabs of coral bedrock have been found as building blocks on Farasan in several locations but are likely to date into much later periods (JE0097, Meredith-Williams et al. 2013, Fig. 4; JW1813, Williams 2011, Fig. 30).

The lack of habitation areas makes the Farasan Islands even more complicated in terms of mobility and sedentarism as we simply do not know where the creators of the +3000 shell mounds have spent most of their time or where they slept. The small amount of artefacts that were found in the middens do not suggest that a lot of other things apart from shell processing have happened there. The postholes could mean some kind of structure but they are not found as frequently as on other sites. We can expect that the settlements were somewhere inland and that the shellfish meat would have been transported to these places. Some shell mounds appear in clusters rather than along the shoreline, which is mostly the case in Khur Maadi and the island Saqid in the North. Here, equally little evidence for habitational sites was found. During the fieldwork of 2013 and 2014, traces of burnt coral bedrock were found inland and in association with A: shell middens or B: possible freshwater wells. There are no dates available as of yet and the association is based on the close proximity of the features but they could still be of importance for the larger middens on the shorelines. Example A (Fig. 9.10) is a typical shell midden with a species composition similar to other sites (mainly *C. fasciatus*, some *Chama* sp., some *Anadara* sp.) but no detailed analysis has been carried out yet. It is much smaller than other middens and possibly not used for as long. In Fig. 8.4.1 the coastline can be seen in the background with some shell mounds. In the left part of the picture is the shell midden and on the right of the picture, is a circular area of burnt coral bedrock. The track that separates both is of unknown origin.

Example B is less definite association of burnt circular patterns with each other in an area with possible fresh water access. In Fig. 9.11 several circular patches of burnt coral bedrock are visible. Next to the 3 m scale and fairly central to the dark patches is an area of around 10 m^2 of fine sediment. Here no bedrock was found, although only shallow test pits of about 30 cm were dug to investigate this. This patch of fine sediment has similarities to modern areas with fresh water access and it is conveniently close to the shell mounds in Janaba West.

That habitational sites are not close to the sea but closer to areas with fresh water access is not an unlikely assumption. Different to mainland sites, where sites are often found close to a wadi (e.g. Crassard et al. 2006, Tosi and Usai 2003), sites on Farasan would have relied on wells and areas where water-storing plants can grow better. In this context it is possible that in Fig. 9.11 the remains of an oasis are displayed. Between the patches of burnt rock areas of fine sediment was found. Different from the typical sediments on Farasan these patches looked like the result of initial soil development and are very similar to the terra rossa found under some of the shell mounds (Chapter 2). However, if this is the case will need to be assessed through a more thorough analysis of the sediment in future studies. For now the occurrence of burnt patches in clusters is all that can be proven.

Another indicator for a habitational site would be the occurrence of lithic artefacts as they had been found on the mainland (Khalidi 2007). Survey on the Islands has produced evidence of isolated finds of ceramics and lithics, very rarely on the surfaces of shell middens, and more often in other types of locations (Williams 2011). Only small numbers of obsidian artefacts were found also basalt, granite and schist , all of which could only have originated outside of Farasan as there are no basalt or obsidian sources found on the island (Bantan 1999). In this context it is interesting to think about the use of shells as raw material to make artefacts. The use of shells as source for tool manufacture is not unknown (Cuenca-Solana 2014, Fujita 2014, Keegan 1994). Larger shells like *Strombus gigas* have been used as adzes (Pawlik et al. 2015), chisels, gouges or bowls (O'Day and Keegan 2001). Mussels have been used as fishhooks (Rick et al. 2002), knives (Cuenca-Solana et al. 2011), or food containers (Malainey et al. 2014).

In one of the bulk samples from JE0004, a modified *Conus* sp. shell was found that could have been used as a backed blade with a serrated cutting edge (Eva Laurie, pers comm.). Why not more shell artefacts have been found is not clear. It is quite possible that they were not searched for and only the very indicative *Conus* blade was obvious. Also if people predominantly used shells as artefacts, it would still be difficult to find habitational sites with them. The larger part of the island's soil, which is still evident under most shell mounds (Chapter 2), has been eroded and was not protected where there were no shells lying on top of it and preserving it. With the soil removed, the artefacts that could have been stratified within it have either been transported into the ocean or are now lying on top of coral bedrock, which itself is made of fossilised shells (Bantan and Abu-Zied 2013). This means that finding the habitational sites will always be very difficult and no good solution for this has yet been found.

9.4 Summary

This chapter took a wider view of the Red Sea and the Arabian Peninsula to discuss the findings from Farasan in the larger archaeological context of the Arabian Neolithic. The outcomes of this discussion are the following:

1. Environmental data from archaeological sites dating to 6,500 and 4,800 cal BP indicate that throughout the recorded time of coastal exploitation the Farasan Islands were part of an arid landscape. No changes in precipitation or marine

water composition indicative of climatic deterioration were found between the first occurrences of shellfish exploitation and instances of established use of shellfish. In other words, it is unlikely that increased aridity was a cause for the big-scale shellfish exploitation on Farasan.

2. The comparison with coastal sites in eastern Arabia showed similarities in terms of year-round continuity and sustainability of coastal exploitation. Coastal sites in arid landscapes seem less marginal than previously argued. Their reliance on inland sites at higher altitudes and more temperate climate for additional food or fodder sources is not observable.
3. Similarities to east-African sites were found, suggesting that similar subsistence strategies were employed and that a sustainable coastal exploitation was a feature of the whole of the southern Red Sea rather than unique phenomenon that only happened on Farasan. Additionally, connections in lithic technology and obsidian sources indicate strong relations between Africa and Arabia that are now likely to have been enabled by the rich coastal environment.
4. There are many gaps in the research on Farasan and the southern Red Sea. Sites on other islands and their ability to work as maritime stepping stones need to be analysed further. Also the lack of habitational sites prevents any complete analysis of subsistence or mobility patterns. Additionally, the incomplete material culture prohibits a comprehensive interpretation of similarities in lithic technology or other craftwork.

Chapter Ten

Conclusion

10.1 Outcomes of this study

This thesis aimed to assess the role of coastal exploitation in the southern Red Sea. For this, I used the Farasan Islands shell mounds as a fitting example for large-scale accumulation of marine resources. I tested them for seasonal patterns and analysed the overall sustainability of coastal subsistence.

Firstly, I established a method exploring how the marine gastropod *C. fasciatus* can be used as an environmental proxy through the analysis of carbon and oxygen isotope compositions, enabling the reconstruction of palaeotemperature and, subsequently, an estimation of the seasons of harvest for archaeological specimens (**Objective 1**). In combination with this, I developed a statistical method to verify the interpretability of the seasonality data (**Objective 2**). My results showed that in all seasons of the year *C. fasciatus* was gathered (**Objective 3**) and that the environmental conditions for the earlier (6,500 cal BP) and later (4,800 cal BP) sites were consistently arid, indicating that the shift of the ITCZ was not the major cause for the forming of the Farasan shell middens (**Objective 4**). Based on these results, I argued for a sustainable way of coastal exploitation that is likely to be applicable for all of the Farasan archipelago, as well as the Arabian and African coastline of the Red Sea (**Objective 5**).

Given these results, this study contributes to our understanding of shell mound accumulation, stable isotopes from mollusc shells and the coastal exploitation of marine resources.

At the beginning of this study, it was unknown if the shell carbonate of *C. fasciatus* can be used for the analysis of seasonality. Earlier research showed that the knowledge about molluscs and their shell is key to interpreting the isotopic values that derive from it (Bailey et al. 1983, Hallmann et al. 2009, Schöne 2008). Without the support of biological studies about the species, I was able to explore its different growth rates and draw conclusions about its possible behaviour. I showed that its preferred habitat is not necessarily as simple as expected and that it is possibly very mobile.

Preliminary analysis of the growth increments within the shell showed daily growth lines in the adult part and possible daily growth lines in the juvenile part. Visibility of growth increments in the adult shell sections was not always consistent enough for an analysis of each shell. The visibility in juvenile parts was even worse, with lines only visible in areas with carotenoid concentrations. These happen only irregularly, which makes consistent measurement of growth lines nearly impossible.

My measurements of carbon and oxygen isotopes showed that *C. fasciatus* precipitates its shell in equilibrium with the surrounding water. Over 1.5 year period I collected live specimens from Janaba Bay and sampled the stable isotope composition of the last growth increments. I compared it to the isotope composition of the surrounding water and the temperature at the time to show that estimated values and measured values are almost identical (R^2=0.88). The seasonal change in oxygen and hydrogen isotopes from different parts of the archipelago also showed how localised the isotopic composition can be. The values showed that instead of rain or other freshwater inputs it is the evaporation that controls the overall composition of the water. Also the ability to mix with the surrounding Red Sea water has a great influence. This is important for future studies that want to analyse shell mounds from different areas on Farasan.

The statistical support for the interpretation of shell seasonality was a key part of the overall analysis. Without it, the produced season of harvest from shell edge sequences would have been far more subjective and the interpretation be much less robust than it is now. For this study, the reason for the statistical analysis was the inconsistent quality of the oxygen isotope values. But I also showed, that it is useful for and applicable to other shell seasonality studies. The analysis of *C. fasciatus* had to work with little to no knowledge of the gastropod, a precondition that other analyses do not suffer. However, the interpretations in other studies are often not objective but based on estimation. Quantifying the fit of the shell edge sequence to the proposed fit for the seasonal change happening in the shell is an invaluable support to the overall interpretation of the season of harvest. In this study it helped to exclude some shell edge sequences and it also helped to verify the different growth rates happening in the shell.

The resulting seasonality data from shell JW1727 has shown that *C. fasciatus* was gathered in every season of the year, in contrast to what has been assumed by other studies on coastal exploitation in arid landscapes (Williams 2011, Cavulli and Scaruffi 2013). The data suggests that more shellfish was gathered in summer and autumn, when the landscape was probably the driest and other food sources were less abundant. This does imply seasonal subsistence change but it also shows that there were other food sources available in other seasons and that the coastal environment has more to offer than only fish. Additionally, it shows that people most probably stayed on the islands for longer periods than previously thought and constant exchange with the mainland must not have been a necessity. At the same time this exchange cannot be ruled out and people could have constantly moved between the island and the mainland, given that the overall population stayed the same and people were there to collect shellfish.

The comparison of oxygen and carbon isotopes from shells dating to 4,800 cal BP and 6,500 cal BP, different periods with different scales of accumulation, suggested that the overall aridity has not changed. This implies that aridity was not the main driver for large-scale shellfish gathering on Farasan. However, this analysis would have benefitted from more detailed environmental proxies and preferably also proxies that are more closely related to the local precipitation rather than the isotopic composition of the marine environment, where other factors than precipitation come into play.

The above results are applicable to other sites of the region. The seasonality data, together with the environmental data and what is known from the species composition of the sites, indicates a landscape of sustainable coastal subsistence. This is not a great oddity in other places in the world where fish is thought to be only a protein supplement and other terrestrial food is always available. But in arid landscapes where most subsistence theories, especially ones that are applied to the Neolithic, focus on terrestrial food sources, a site with a coastal focus is unusual. If people rather live on the coast and gather shellfish than becoming herders and planting food in the mountains, then this can tell us a lot about shellfish gathering as an alternative food source in other neolithic societies (or any other time period) around the world.

This study aimed to assess three key questions about the Farasan shell mounds that can be addressed with the above results;

a) How fundamental were the shell mounds for the occupation of the islands?

- They were very fundamental. Shellfish provided an all year protein source and were also used seasonally, possibly as an alternative to terrestrial food.

b) Could the shell mounds support a permanent settlement?

- Yes, shellfish were collected in every part of the year and shell size variation did not show any signs of overexploitation. A permanent occupation of the islands was possible but a permanent settlement in one place of the islands cannot be proven because of the lack of habitational structures.

c) Are the accumulations of marine molluscs related to climate change?

- No, from what is known about the isotopic composition of shells, the surrounding marine environment did not experience changes in salinity between the two analysed periods. This indicates that precipitation and freshwater inflow into the Red Sea did not occur on a significant scale.

10.2 Future research

During this study there were several obvious gaps in the research that need following up in the future. The seasonality study showed an emphasis in shellfish collection in summer and autumn. What is being eaten in the other times of the year?

There are fish remains in the shell mounds that would help with the analysis. Stable isotope research on the fish otoliths could be a very useful addition to the dataset and a different seasonal distribution would make for interesting theories about how they were valued in comparison to shellfish. In modern times the seasonal exploitation of fish is part of the Farasan culture. The targeted exploitation of *Hipposcarus harid* (longnose parrotfish) is a seasonal festival at the end of spring (Gladstone 1996). The fishermen link the occurrence of this species to the spawning of the corals. However, underwater surveys by Gladstone showed that the species is abundant before and after the festivals, giving the timing of the tradition a more arbitrary character. Linking such a tradition to the exploitation of fish and shellfish during the mid-Holocene would be extremely interesting. A celebration of fish resources at the end of spring would fit with the start of the overall fishing season in summer and autumn as it was seen in JW1727.

But other food sources apart from fish or shellfish must have been consumed. Charcoal remains in the middens suggest that burning material and some kind of vegetation was available. A more thorough analysis of this material could reveal which plants were used most often and give insight into the overall environment of Farasan.

In addition, the soil remains that are preserved below the middens indicate some degree of fertile soils that are now eroded but were once available. Phytolith analysis in these soils is extremely difficult as the arid environment is unfavourable for their preservation and the results will be extremely biased. Also, using this approach it would mostly be limited to understanding the vegetation from when the middens were started rather than how the vegetation might have changed throughout the occupation period.

Another aspect that will need future analyses is the variation in seasonal enrichment in $\delta^{18}O$ of the water that the shells live in. Shells in Khur Maadi show different seasonal amplitudes because their environment is more susceptible to evaporation processes. This change in amplitudes needs further analysis, as it might help us to understand how the molluscs react to evaporation processes in the water and it might also give us an indication of the differences between the enclosed shallow water areas and the more exposed ones like Jabana Bay.

Even more promising is possibility that this change in seasonal amplitude can be used as an indicator of how enclosed Khur Maadi Bay was in different periods. Geological studies, as well as the distribution of some inland shell mounds, suggest that Khur Maadi Bay and Janaba Bay used to be connected, splitting the main island, Farasan Kabir, in half. It would be possible to accurately date the divide into Khur Maadi Bay and Janaba Bay by comparing the seasonal amplitudes recorded in shells from different sites, in combination with radiocarbon dates from the same sites. Following this we could assess how the exploitation of the bay areas changes. The divide could have initiated some of the large scale exploitation we saw in KM1057.

The application of seasonal signal to reconstruct accumulation rates as shown here has big potential for shell midden sites all over the world. Possible sequential seasons have potentially been found in the Culverwell midden (Mannino et al. 2003) and there is no reason why similar applications cannot be made. In particular, rapidly accumulated shell midden sites that are less disturbed should have a sequential deposition of seasons preserved, provided that the stratigraphic information is being recorded for the analysed shells. However, for this more research needs to be done and more care needs to be taken when excavating the shell deposits. As was indicated by the difference of general accumulation rates of JW1727 and specific rates in layer 8 of JW1727, it is unlikely that just because stratigraphic context for shells is provided this will also result in an alignment of stratigraphic sequence and seasonal sequence. There is no way to really know if layers have been disturbed and if what is being sampled is actually the base or the top of the deposit or unless the middens are being excavated horizontally and by single contexts. This is extremely difficult in the Farasan middens as they do rarely have any sediment matrix and sometimes only show differences when seen in the section.

One of the major problems with this approach is the small numbers of shells that can be analysed for seasonality. In an ideal world, financial and temporal constraints would not exist for this research and every shell could be analysed with no difficulties. Even small shell deposits would become visible and seasonal sub-layers could be analysed similar to differences in particle size of sediment colour. The preliminary research using Laser Induced Breakdown Spectroscopy is very promising and will be crucial for future research by increasing sampling resolution and the number of sampled shells at a little cost. This requires a thorough calibration of the Mg/Ca ratio and temperature change as well as metabolic influences that can have an effect on the results. Until then, the occasional lucky find in combination with radiocarbon dates and other methods of archaeological science will be needed to be explored.

Future studies that include the Arabian mainland and the wider area of the southern Red Sea will have to also include the Dahlak Islands in Africa. The similarity to Farasan in lithic technology and shell mound size, abundance and distribution is more than striking and needs further analysis. If more similarities can be found by excavation, a better claim for a strong relation between coastal sites on either side of the Red Sea can be made.

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