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# Exploring Accumulation Rates of Shell Deposits Through Seasonality Data

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**Abstract** Shell middens are often analysed as the result of short- or long-term depositional activities. In order to confidently interpret such deposits, it is necessary to have accurate estimations of shell accumulation rates, most commonly produced by radiocarbon dates. This paper introduces the application of seasonality data as a temporal measurement of short-term shell deposition. This gives access to an additional estimate of shell accumulation rates, which work on a shorter timescale than can be analysed through radiocarbon dating. We focus on shell deposits on the Farasan Islands, Saudi Arabia, which comprise over 3000 shell midden sites dating to the mid-Holocene (6500–4500 calBP). One site (JW1727) was chosen to (1) explore the potential of seasonality data to reconstruct accumulation rates, (2) analyse the intensity of exploitation and (3) assess the visibility of short-term shellfish deposits. Stable oxygen isotope values ($\delta^{18}O$) were obtained from the marine gastropod *Conomurex fasciatus* (Born 1778), representing 72 % of the shell weight of JW1727, to reconstruct season of capture. Seasonality data was grouped by their spatial distribution, which allowed successive episodes of deposition within a stratigraphic sequence to be connected. This allowed us to make an estimation of exploited shell meat of ~200 kg over a 7-month period (~400 shells/day). We argue that excavation methods and low resolution stratigraphic data cause imprecision in the seasonality data and the low visibility of rapidly accumulated shell deposits. Also, an increase of analysed shells per layer is key to understanding the seasonal brickwork of more middens in the future.

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## Introduction

Shell midden deposits are valuable records of the human past and often supply the scaffolds on which to build our understanding of prehistoric coastlines. They often provide exceptional preservation conditions for artefacts as well as human and animal remains. The structure of their shell matrix itself is equally rich in archaeological information. Hence, the study of shell middens is also closely linked to the studies of layer structure and deposition (Briz Godino *et al.* 2011; Claassen 1998; Stein 1992; Stein *et al.* 2003; Thompson and Andrus 2011; Villagran *et al.* 2011; Waselkov 1987). More specifically, the analysis of shell accumulation rates has led to comparisons of population sizes, exploitation intensities, the identification of occupation hiatuses or depositional disturbances, as well as objective comparisons of human activities between sites (Jerardino 2015; Jew *et al.* 2015; Kennett *et al.* 2011; Lombardo *et al.* 2013; Stein *et al.* 2003).

In particular, rapidly accumulated shell midden sites (<100 years) provide a scale and resolution that allow the analysis of site formation in high detail. In part, this is due to the favourable preservation conditions provided by the hard carbonate component of shells and the abundance of shells that are deposited. Additionally, rapidly accumulated shell deposits provide immediate shelter for underlying shell layers, which enables the mound to grow more substantially than slowly accumulated deposits, whose shells are exposed to erosion for longer periods.

Exceptionally large shell deposits are often interpreted as having some sort of cultural significance because of their monumental size or appearance (Faulkner 2009; Fish *et al.* 2013; Marquardt 2010). Ritual intentions and social agendas (such as feasting) have been considered as the possible drivers for such intensive shellfish accumulation, but more domestic contexts are also possible (Hayden 2014; McNiven 2012; Russo and Heide 2001; Saunders 2004; Saunders and Russo 2011; Schwadron 2010).

In order to make the cultural processes behind rapid shell mound accumulation more visible, Stein *et al.* (2003) aimed to assess the different degrees of layer accumulation by applying stratigraphically detailed sampling methods to analyse radiocarbon ($^{14}C$) dates. This makes it possible to narrow down the time span of shell deposition for single excavation units and to determine the accumulation rate of single layers (or arbitrary spits when changes in colour, texture, content, *etc.* do not allow a definition of layer boundaries). More recently, high-resolution $^{14}C$ dates and the use of Bayesian modelling have allowed a more accurate estimation of site chronologies as a whole but also of the accumulation rates of single layers in the shell deposit (Jerardino 2015; Jew *et al.* 2015; Kennett *et al.* 2011; Lombardo *et al.* 2013; Stein *et al.* 2003).

However, individual or short-term episodes of deposition can often be too ephemeral to be accurately defined through radiocarbon dates. To be able to measure or analyse these more short-term deposits, it is necessary to work on an appropriate time scale (Bailey 2007). In this context, Stein *et al.* (2003) found that some layers were deposited almost ‘instantly’. Those layers theoretically had an infinite accumulation rate as the initial and terminal radiocarbon dates were identical (see also Morrison 2014 for negative accumulation rates). Radiocarbon dating is not sufficiently accurate to distinguish the beginning and end dates of these short-term depositions and arguably works on a resolution that is not applicable to all rates of shell accumulation, particularly the rates that are closest to individual human activities.

In this paper, we provide new information on accumulation rates by employing seasonality proxies from shell deposits in addition to radiocarbon data. This enables us to engage with the deposit on a shorter timescale and thus at a higher resolution than was previously possible by only using radiocarbon dates. We show that it is possible to assess the accumulation rate of shell deposits at a monthly resolution and to identify rapidly accumulated deposits using seasonality data acquired from archaeological shells. Subsequently, we show that the visibility of such deposits is not only linked to their high accumulation rate but also strongly connected to layer preservation, as well as excavation and sampling methods. Thereby, we gain a more detailed understanding of patterns of shell deposition and therefore of human shellfish consumption practices.

We chose to examine the shell mound JW1727 on the Farasan Islands (Saudi Arabia), a large but short-lived shell midden (Fig. 1). The site itself has a volume of ~160 $m^3$ while radiocarbon dates suggest only 16–88 years of accumulation time (65.4 and 95.4 % confidence, respectively) (Table 1, Fig. 2; see also supplementary dataset 1). The proximity of the individual radiocarbon dates makes it difficult to further refine accumulation rates. Hence, we additionally employ sequential stable oxygen isotope ratios ($\delta^{18}O$) of archaeological *C. fasciatus* shells from JW1727. These shells have been acquired using a sampling approach in the field that allows seasonality data to be used to assess accumulation rates with finer resolution than can be obtained from sequences of radiocarbon dates.

## Seasonality and Accumulation Rates

Shell deposits that accumulated over a short time span (within 1 year) are difficult to identify using radiocarbon dating, and this has important consequences for determining accumulation rates and, for example, the study of feasting activities. It was for this purpose that seasonality data was first applied to reveal the temporal structure of shell middens of the Sapelo Island shell midden complex (Thompson and Andrus 2011). Thompson and Andrus (2011) applied seasonality data from shell layers to distinguish between gradual depositions of a small-scale but long-term activity (expressed as multi-seasonal signal) and rapid depositions of a large-scale but short-term activity (expressed as a single-season signal). When a layer with a single-season result can be identified within layers of long-term, multi-seasonal deposits, they argue that this is evidence of feasting activities. This analysis was closely linked to the stratigraphic context of the sampled shells and made possible by a detailed sampling technique in the field.

While this approach is valuable in identifying single-season accumulations within a deposit, it does not enable an estimation of accumulation rate because the temporal component is restricted to one point in time. However, when the beginning and the end of the unit can be differentiated by season, estimating the accumulation rates of single excavation units may be possible. This provides a specific time range rather than just the one point in time that is a single season.

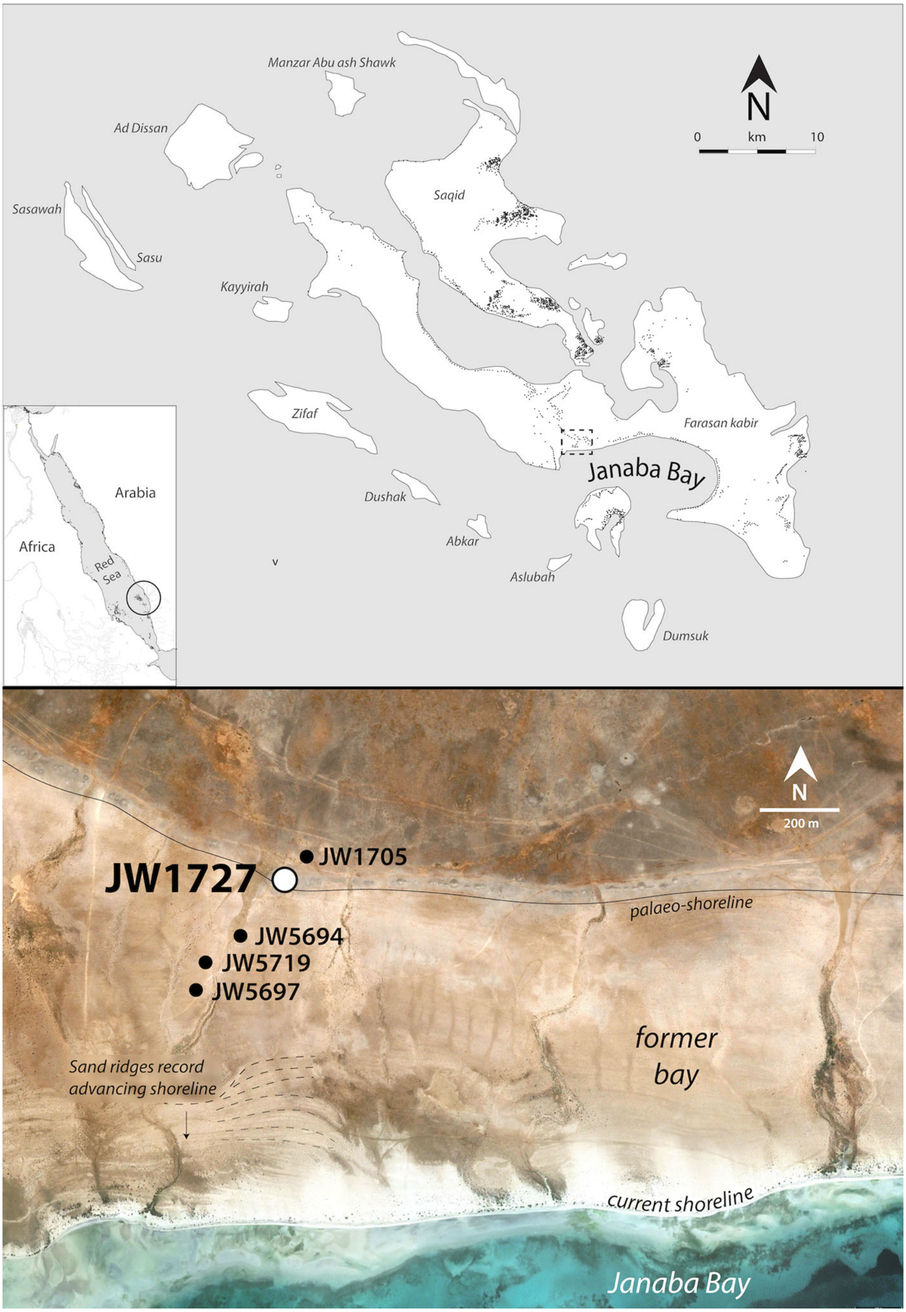


**Fig. 1** Location of Farasan Islands and research area (*dotted rectangle*). *Below*: *black dots* indicate excavated shell midden sites

Expanding on Thompson and Andrus (2011), we developed a sampling approach that enables the detection of short-term accumulations of shell and enables the measurement of accumulation rates on a different scale than is possible with radiocarbon

**Table 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

| Lab no. | Layer (depth) | $^{14}$C-Age | Mar. Res. Corr. | calBP Range 2σ | Material | Species |
|---|---|---|---|---|---|---|
| OxA-28,009 | 2 (0.13 m) | 4851 ± 31 | −123 ± 28 | 5108–4873 | Shell | Mussel (*Brachidontes* sp.) |
| OxA-27,890 | 17 (0.95 m) | 4202 ± 29 | | 4835–4660 | Charcoal | Unidentified |
| OxA-27,889 | 23 (1.68 m) | 4287 ± 29 | | 4861–4838 | Charcoal | Unidentified |
| OxA-28,617 | 23 (1.68 m) | 4701 ± 28 | −123 ± 28 | 4907–4735 | Shell | Mussel (*Brachidontes* sp.) |
| OxA-31169 | 27 (basal) | 5044 ± 35 | −123 ± 28 | 5444–5064 | Shell | Mussel (*Brachidontes* sp.) |

dates. We base our interpretations on the groupings of shell samples that produce the same seasonal signal, as well as the distribution of these groupings within the layer (Fig. 3). Theoretically, the simplest interpretation is a short-term accumulation in the form of multiple shells with the same season of harvest seemingly instantly deposited in a group within one complete layer (Fig. 3a). This interpretation becomes dramatically more certain with an increasing number of analysed shells.

Less rapidly accumulated deposits or thicker layers would show a more developed sequence of seasons (Fig. 3b). The seasonality results would show a seasonal range gradually developing throughout the deposit. In the absence of more detailed stratigraphic information, multiple seasons within a stratigraphically defined layer should be interpreted as a palimpsest resulting from slow accumulation or disturbance. However, if a group of shells indicating one season is overlaid by a group of shells indicating the following season, it becomes more likely that the deposits reflect a time series of successive seasonal events. This would further strengthen the interpretation that the deposits represent continuous, or repeated, occupation of the midden by the same group of people.

When the seasons of death are not sequential, it is likely that the shells are within a disturbed deposit (where shells from different accumulation events have been mixed) or that shells were accumulated with a very low rate and the sampling resolution is not high enough to capture the sequence of individual episodes (Fig. 3c).

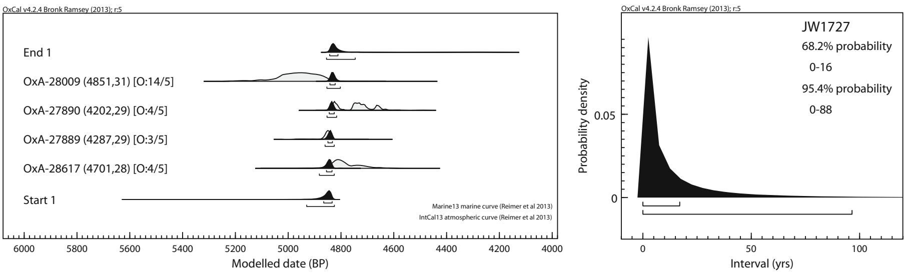


**Fig. 2** Radiocarbon dates and probabilities of accumulation periods for JW1727 based on a *t*-type general outlier model with prior probability set at 0.05 (Bronk Ramsey and Lee 2013). The values in *rectangular brackets* indicate the posterior and prior outlier results. See details for Bayesian model used in OxCal v4.2.4 in the supplementary dataset 1

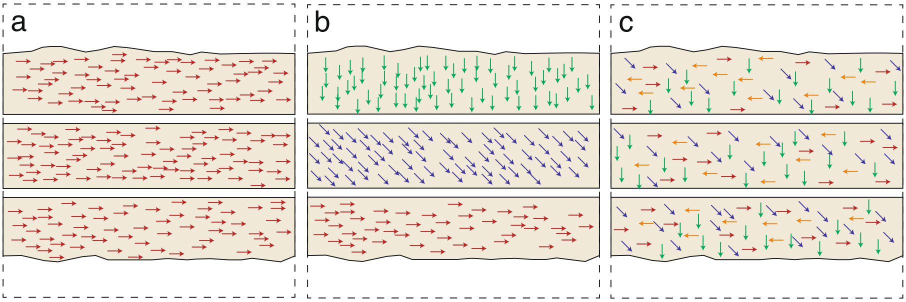


**Fig. 3** Theoretical model of distribution of seasonal signals throughout a rapidly accumulated shell deposit. Direction of *arrows* indicates seasons. **a** Single-season deposit. **b** Succession of seasons throughout a layer divided by spits. **c** Mixed seasons within one layer due to slow accumulation or mixed deposits

Following this approach, a single-season deposit can be identified and layers where the seasonal signals are grouped in succession (for example, a group of shells harvested in spring at the base followed by a group of shells harvested in summer at the top) can help to estimate how much shellfish was exploited in a certain amount of time, given that the stratigraphic order is coherent.

This provides insight into the richness of the local molluscan habitat, and into the quantity of food consumed before the location was deemed to be no longer profitable.

Given these complexities, there are two key factors to this approach of grouping shells by their position in the layer, (a) a record of the stratigraphy and sample location during shell mound excavation and (b) a large number of sampled and analysed specimens per layer. No grouping of shells should be trusted if they are stratigraphically disconnected or are too small to rule out coincidental similarities.

Following this, multi-season result based on shells within one single spit can (and should) be interpreted as the result of disturbance or as a period of intermittent or limited activity, with long time periods (*i.e.* longer than a season) between small-scale deposition events. Conversely, a layer with only one shell from spring at the base and only one shell from spring at the top is potentially still a multi-season layer, considering the chance of this happening by coincidence when only two shells were sampled.

## Archaeological Background and Sampling Method

### Site Background

The Farasan Islands are situated about 40 km west of the Tihama coastline of Southwest Saudi Arabia (Fig. 1) and are the location of over 3000 shell midden sites (Bailey *et al.* 2013; Meredith-Williams *et al.* 2014b). The majority of sites date to the mid-Holocene (6500–4500 cal BP) and are likely to be the result of a subsistence strategy that includes highly productive shellfish gathering and the subsequent deposition in the form of large shell mounds along the palaeo-shorelines.

Shell mound JW1727 is located in the northwestern part of Janaba Bay (Fig. 1). This part of the bay used to be part of a palaeo-channel that connected Janaba Bay and Khur Maadi Bay. The combination of a mid-Holocene highstand in sea level and tectonic uplift has raised this channel above the sea level and put JW1727 at a distance of

0.75 km from the current shoreline. The mound is located on a sand ridge on a palaeo-shoreline along which are several dozen similar shell middens.

Despite its size and prominent position in the landscape, the radiocarbon dates indicate a very short accumulation period of less than two decades. Samples from layers 2, 17 and 23 all dated to around 4800 cal BP (Table 1, Fig. 2; see also supplementary dataset 1).

During excavations in 2013, a 1-m wide and 10-m long trench was excavated from the rim of the mound towards the centre (Meredith-Williams *et al.* 2014a). A column of bulk samples (20 cm × 20 cm) was collected at the centre of the mound to avoid more disturbed areas at the rim. Bulk samples were taken in spits of 10 cm depth or less when the layer size did not exceed 10 cm. Generally, JW1727 shows a clear dominance of *C. fasciatus* shells (72 % of weight) in combination with *Pinctada* sp. (5 %) and *Arca avellana* (6 %). However, layers were usually composed of one or two species with the exception of disturbed layers at the top and the rim of the mound (Fig. 4) for which current analyses are still ongoing.

## Sample Origin

Overall, four layers (8, 13, 18 and 20; Fig. 4) of JW1727 were chosen to assess accumulation rates. The shell assemblages from each of the sampled layers predominantly consist of *C. fasciatus* (layer 8: 98 %; layer 13: 83 %; layer 18: 93 %; layer 20: 73 %). Shells were not taken from bulk samples but were directly picked out of the exposed and cleaned section to get an exact sample location. We divided distinct layers of the stratigraphy into initial, intermediate and terminal spits, ('base', 'centre' and 'top', respectively) (Table 2). Excavation showed that visibly identifiable layers in the middens are frequent and usually thicker than 5 cm in size, which allows the layer to be sampled as 3 spits. A limiting factor here is the size of *C. fasciatus* shells (3–4 cm), which does not realistically make sampling on a smaller scale at all feasible.

Layer 8 is a distinct layer of clast-supported *C. fasciatus* shells with a thickness between 11 and 8 cm. It overlies a layer of bivalves (layer 9) and is covered by a dense layer of charcoal (layer 7). Both borders are distinct and no mixing seems to have occurred. Thirty-two 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.

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 few shell edges in a condition suitable for analysis. While the middle and the base layer both provided 7 shells, the top layer only provided 3. Layer 13 is slightly larger than layer 8 with a thickness of 10–15 cm. Additionally, the composition is very similar, consisting of mostly *C. fasciatus* and has little to no sedimentary matrix. It is covered by a *C. fasciatus* layer mixed with ash (layer 12) and overlies another *C. fasciatus* layer with a distinct orange staining of unknown origin (layer 14).

Layer 18 is a *C. fasciatus* layer with little to no sedimentary matrix and pristine preservation of shells. Compared to layers 8 and 13, it is much thicker with a thickness of 25 cm and contains distinct lenses of charcoal and bivalves. Such lenses were not found in layers 8 or 13 and suggest that, despite first impressions, layer 18 might not be a single episode layer but actually several *C. fasciatus* layers that can only be distinctly

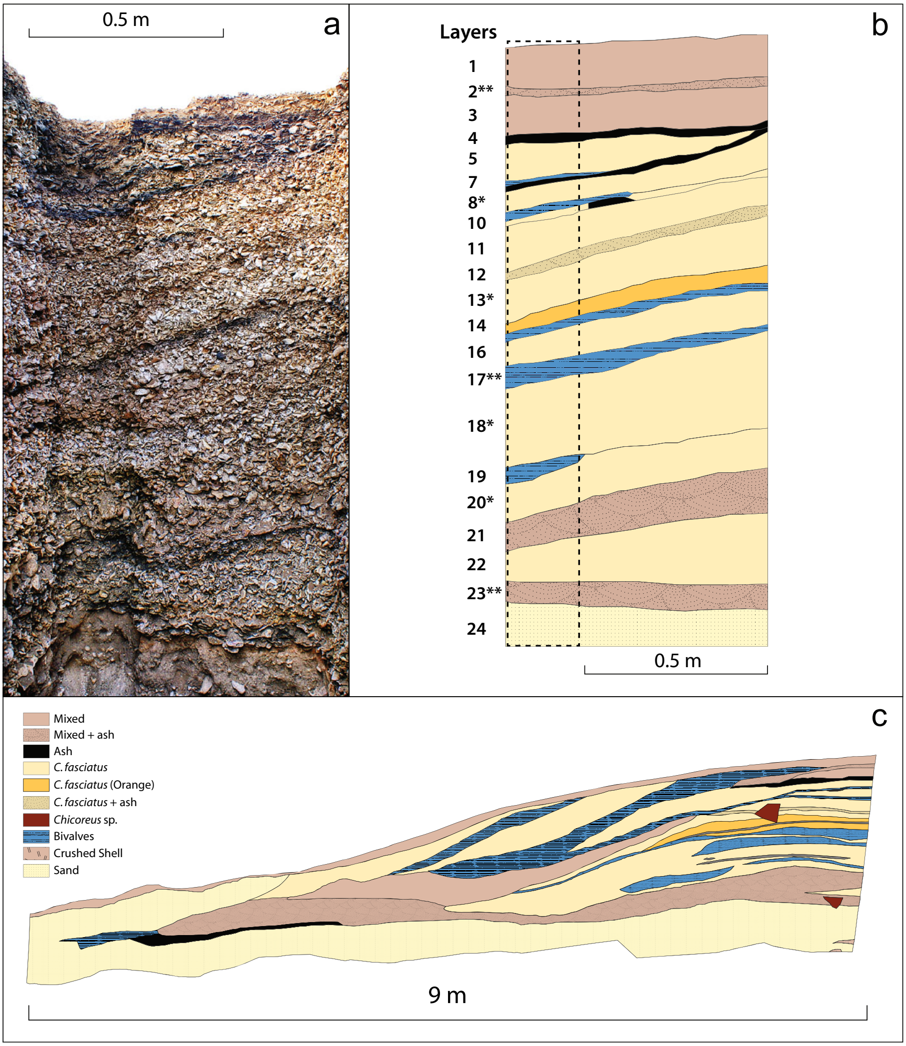


**Fig. 4** **a** Exposed central section of JW1727. **b** Section drawing of central section (*asterisk* indicates layers sampled for seasonality, *two asterisks* indicate layers sampled for radiocarbon), *box with dotted lines* indicates location of bulk samples for species analysis. **c** Drawing of lateral section from outside of the mound (*left*) to the inside of the mound (*right*)

separated in locations with shell accumulations of different species composition. Again, shells from layer 18 have been chosen for analysis from the top ($n = 3$), the middle ($n = 8$) and the bottom ($n = 7$); however, due to the apparently 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.* layers 8 and 13).

In Layer 20, it was only possible to sample at the top ($n = 7$) and the base ($n = 8$) due to its thinness. It has no sedimentary matrix and shell fragmentation is very low. Some filling with ash from the overlying ash layer (layer 19) occurred sporadically, but otherwise, the shells are in pristine condition.

**Table 2** Numbers of collected, sampled and successfully analysed *C. fasciatus* shells per layer that provided a seasonal signal. Also, the MNI from bulk samples of the layers is reported. Note that the stratigraphic resolution of the bulk samples is lower than the hand-picked shells

| Layer | MNI in layer | Sublayers | Hand collected | Sampled | Produced interpretable result | Success (%) |
|---|---|---|---|---|---|---|
| 8 | 317 | Top | 9 | 5 | 5 | 100 |
| | | Middle | 16 | 8 | 7 | 88 |
| | | Base | 7 | 6 | 4 | 67 |
| 13 | 73 | Top | 3 | 3 | 3 | 100 |
| | | Middle | 13 | 7 | 6 | 86 |
| | | Base | 7 | 7 | 3 | 43 |
| 18 | 484 | Top | 9 | 6 | 6 | 100 |
| | | Middle | 13 | 8 | 7 | 88 |
| | | Base | 10 | 7 | 7 | 100 |
| 20 | 220 | Top | 7 | 7 | 5 | 71 |
| | | Base | 8 | 8 | 4 | 50 |
| Total | 1094 | 11 | 102 | 72 | 57 | Average 79 |

## Measurement of Oxygen Isotope Ratios

Stable oxygen isotope ratios to determine the season of capture have successfully been applied to shell midden sites around the world (Colonese *et al.* 2012; Eerkens *et al.* 2013; Jew *et al.* 2013; Mannino *et al.* 2003; Schweikhardt *et al.* 2011). Seasonally changing $\delta^{18}O$ values are related to changes in temperature as well as the isotope composition of the ambient water that the shellfish live in, which itself is controlled by evaporation, precipitation and freshwater inflow (Leng and Lewis 2014). Measuring stable oxygen isotope ratios of mollusc shell carbonate thus provide information on the seasonal changes in the local environment. Additionally, the terminal data points from the very shell edge can be used to determine in which of the seasons the animal stopped precipitating carbonate (*i.e.* the time of death and collection by humans).

Initial research on the potential of *C. fasciatus* shells as palaeo-climate and seasonality proxy has previously been carried out by Hausmann *et al.* (2016), and here, it provides the foundation for the determination of season of death. Hausmann *et al.* tracked the seasonal change in $\delta^{18}O$ values found in terminal growth increments of modern *C. fasciatus* specimens throughout the year. Values from shell carbonate were compared to estimated $\delta^{18}O$ values based on temperature change and changes in the water composition. They were found to be in good correlation of $R^2 = 0.88$. The seasonal variation was similar to the variation found in shells from archaeological contexts (shell middens JW1727 and JE0087). This is connected to the low rates of degradation found in archaeological samples. Raman analysis determined that the shells from modern as well as archaeological context were pure aragonite (Hausmann *et al.* 2016). Based on these results, we used the data from Hausmann *et al.* (2016) to provide a seasonal reference curve to which we could compare the sequential $\delta^{18}O$ values from archaeological shells and determine the season of death.

The $\delta^{18}O$ values in this study were taken from terminal lip parts of adult shells (as described in Hausmann *et al.* (2016) (Fig. 6). Shells were cleaned, cut parallel to the growth direction using a diamond saw, and then put on glass slides using epoxy resin. After the hardening of the resin, the shells were cut again, parallel to the first cut, leaving a 3-mm thick section of the shell on the glass slide. The sections were then ground with metallographic grinding paper (P800, P1250, P2500) and polished (TexMet cloth and 3-μm diamond paste and MetaDi fluid) to reveal growth lines on the sections. Polished sections were recorded using a Zeiss Axio-scope microscope. Following this, the slides were sampled with a 0.4-mm drill bit on a lever-controlled Dremel drill setup for vertical drilling. Considering the estimated growth rate of adult specimens (~13 mm/year; Hausmann *et al.* 2016), the 0.4-mm sample area should represent about 2 weeks of shell growth; however, this is a tentative estimate as no growth study has previously been carried out on *C. fasciatus*. Holes were drilled with a depth of ~2 mm and where possible in a straight line following the direction of growth. Movement of the sample location along a growth line was necessary in some cases due to the changes in growth direction that can occur on the shell lip (Fig. 5). Samples usually had gaps of 0–0.2 mm between them, although larger gaps (3–4 mm) were possible in juvenile parts of the shells. Generally, sequences of 10–15 samples were taken (shortest sequence: 7; longest sequence: 28).

Juvenile specimens do not have a distinct lip. After cleaning in ultra-pure water and subsequent drying overnight, they were sampled perpendicularly to the growth lines on the outside of the shell using a 9-mm hand-held Dremel drill.

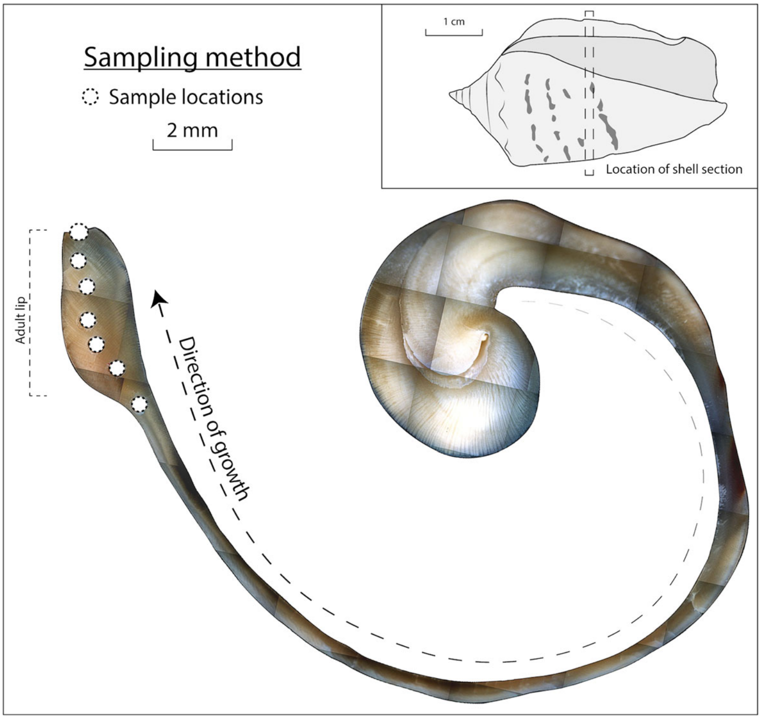


**Fig. 5** Sampling method on archaeological *C. fasciatus* shell section and position of section within shell

The carbonate powder of juvenile and adult specimens was analysed at the Stable Isotope Facility of the British Geological Survey. Approximately 50–100 micrograms of carbonate are used for isotope analysis using an IsoPrime dual inlet mass spectrometer plus Multiprep device. Samples are loaded into glass vials and sealed with septa. The automated system evacuates vials and delivers anhydrous phosphoric acid to the carbonate at 90 °C. The evolved $CO_2$ is collected for 15 min, cryogenically cleaned and passed to the mass spectrometer. Isotope values ($\delta^{18}O$) are reported as per mille (‰) deviations of the isotopic ratio ($^{18}O/^{16}O$) calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS-19. The CaCO3-acid fractionation factor applied to the gas values is 1.00798. Due to the long run time of 21 h, a drift correction is applied across the run, calculated using the standards that bracket the samples. The Craig correction is also applied to account for $^{17}O$. The average analytical reproducibility of the standard calcite (KCM) is 0.05‰ for $\delta^{18}O$.

## Results

In total, 57 shells from four layers and 11 spits in JW1727 produced an interpretable seasonal signal (79 % of analysed specimens) (see supplementary dataset 2). We structured the seasonal signals by the position of the sampled molluscs within the layer. Despite the pristine conditions of the sampled layers that suggest rapid accumulation, no layer contained shells from only one season. Of the four layers analysed, three showed similar seasonal distributions within their spits, which covered most of the year and did not suggest an 'instant deposition' or enable an assessment of accumulation rates. However, layer 8 produced seasonal signals that changed in accordance with the sample position within the layer, making it possible to measure the accumulation rate that occurred during its deposition.

In general, the seasons of exploitation in layer 8 are between spring-summer and autumn-winter. But by separating analysed shells into spits, a gradual change of seasons from the top of the layer towards the base can be seen (Fig. 6). The base of the layer is characterised by shells with ranges of $\delta^{18}O$ edge values between −1.3‰ and −2.0‰, indicating early summer and summer exploitation. This is followed by shells from the summer to autumn-winter with edge values ranging between −1.3‰ and −1.8‰ in the middle part of layer 8. The top is characterised by shell edge sequences that all follow a trend from typical summer values at −1.5‰ to around −0.9‰, indicating a gradual cooling of the sea surface water. Terminal edge values put them into autumn and autumn-winter.

Sample sequences of shells in layer 13 show a wider range of harvesting seasons but also a peak in autumn and autumn-winter (Fig. 6). No obvious gradual change in season with the succession through the layer is apparent. Shells within spits indicate seasons of capture with significant gaps in between. Only shells in the middle show somewhat of a continuity with autumn to winter representation.

The seasonal signals of layer 18 are well distributed with a peak in summer-autumn (Fig. 6). Every season but spring is represented and no gradual change from one spit to another is apparent. The shells of layer 20 are distributed with an increased exploitation

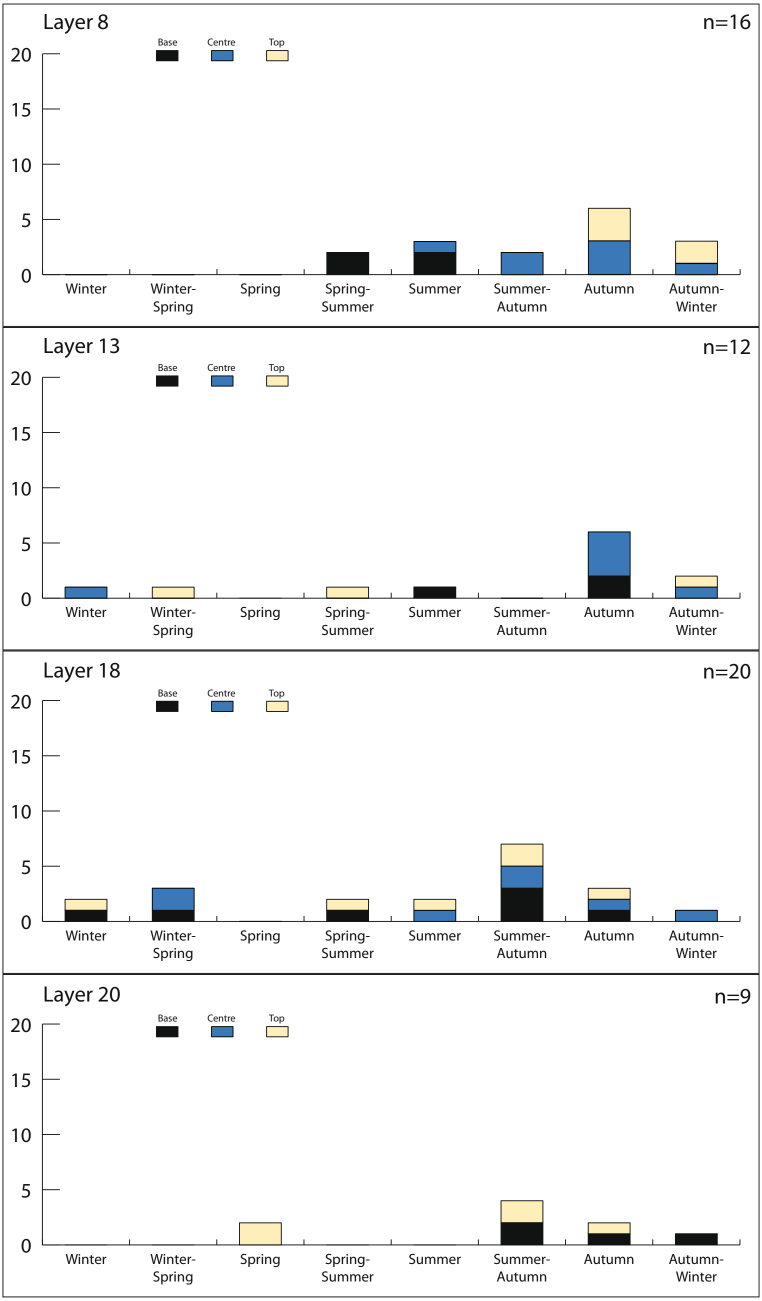


**Fig. 6** Seasonality results from analysed layers in JW1727. *x*-axis describes seasons throughout the year; *y*-axis describes number of analysed shells that fell into the seasonal category

in summer and autumn (Fig. 6). The seasons indicated by shells from the base of the layer are restricted to late summer and autumn, while shells from the top of the layer plot in the seasons from late summer to late autumn and additionally in spring.

## Discussion

### Introduction

In this discussion, we aim to (1) discuss the possibility of revealing accumulation patterns in the record, (2) assess accumulation rates from seasonality data in light of rates derived from radiocarbon dates and (3) discuss our sampling approach and the invisibility of rapidly accumulated layers due to excavation methods.

### Preservation of Accumulation Record

We were able to locate an individual accumulation episode within the shell deposit in the form of layer 8, which showed a gradual change in season of harvest from spring-summer to autumn-winter. The occurrence of shell exploitation happening over several months is in itself not a surprise. It is implied by the short time span for the mound as a whole defined by radiocarbon dates. However, the preservation of this sequential deposition throughout the spits is remarkable.

Formation processes from the initial deposition through to the general taphonomy of shell deposits have been the centre of much discussion (Bailey 2007; Holdaway and Wandsnider 2008; Koppel *et al*. 2016; Larsen *et al*. 2016; Magnani and Schroder 2015; Shiner *et al*. 2007). Most scholars agree that the 'layer cake' character, as suggested by horizontally layered deposits, is not the result of laminar depositions as they are found in, for instance, lake deposits but rather the result of post-depositional processes, such as strong weather, deflation or human activity, that spread out and mixed up previously deposited shells.

Despite this, the seasonality data found in layer 8 shows a linear succession of shells from the base to the top, which seems to have been unaffected by these post-depositional effects and implies laminarity of the deposit. At this point, it is necessary to mention the possibility that the shells are grouped this way because of pure coincidence and layer 8 is in fact disturbed. However, since all 16 analysed shells revealed the same seasonality data, we feel confident that this layer is not the result of such post-depositional processes.

Interestingly, a similar situation as in JW1727 was found in the Culverwell midden (UK) (Mannino and Thomas 2001), where a decrease in shell sizes throughout sequential spits of the layer 8 indicated intense and continuous exploitation (not to be confused with the layer 8 of this study). This was accompanied by a gradual 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. However, the lack of more detailed stratigraphic information about where in each layer the shells originated prevents comparing the stratigraphic and isotopic particulars of each shell.

Contrary to the post-depositional effects above, Thompson and Andrus (2011) found grouped seasonal signals in the Sapelo Island shell rings that would not have occurred in completely disturbed deposits.

As a result of this study, as well as that of Mannino and Thomas (2001) and Thompson and Andrus (2011), we argue here that while we acknowledge the effects of taphonomic processes on most of the deposited shell layers, we also recognise that they do not affect every layer in the same way and leave the chance of less (or un-)disturbed material.

## Accumulation Rates Based on Seasonality

Based on the exploitation period represented by the seasons of harvest within layer 8 and the volume of shell deposit represented by the layer, we came to an estimate of daily deposition rate.

Figure 7 shows the gradual change of shell edge sequences throughout layer 8 on the estimated $\delta^{18}O$ values based on the modern reference (Hausmann *et al.* 2016). While the sequences clearly belong to specific seasons, the number of months of the overall time period is more difficult to ascertain. In particular, the fairly stable $\delta^{18}O$ values during summer make it difficult to accurately determine the occupation time. Using the beginning and the end of summer as earliest and latest possible start of deposition, different time periods are possible (min: 3 months, max: 9 months). However, based on the individual growth rates of the shells, the sequences in general make 7 months the most likely time period. Combining this period of 7 months with the estimated volume of layer 8, we can estimate a value for the amount of shell that was harvested per day.

Layer 8 is represented as a 10-cm thick section of a somewhat conical layer. The assumption of a conical shape is based on the general circular shape of the mound, the overall stratigraphic sequence, and that the layer is thickest in the middle of the mound, lensing out towards the edges. This would mean that layer 8 had a radius of 1.4 m and a volume of 0.63 $m^3$. After field observations by Williams (2011) and Hausmann (2015), this is equivalent to ~600 kg of empty shell weight, producing a total weight of ~200 kg of shell meat. This total amount, divided by the estimate of 210 days (7 months) of occupation time, would result in about 1 kg of procured shell meat per day. This is equivalent to about 400 individual specimens of *C. fasciatus* (a volume of 4–5 l or one gallon). Modern ethnographic analogies for *C. fasciatus* collection are lacking (Bailey *et al.* 2013); thus, we will not engage in estimating the time and effort of collecting 400 specimens. However, the volume estimate indicates that it is an amount of shellfish that can easily be transported by one person and can be encountered in easily accessible shallow water areas (Bailey *et al.* 2013).

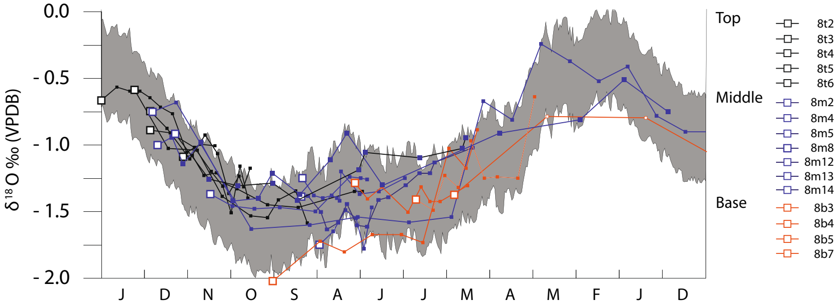


**Fig. 7** Shell edge sequences of layer 8 plotted on the estimated $\delta^{18}O$ values (*grey*) from Janaba Bay throughout the year

## Comparing Accumulation Rates

Since seasonality data and radiocarbon dates work on different time scales, they cannot be used interchangeably. But to gain some insight into the rate of accumulation in layer 8 in relation to the average accumulation rate of JW1727, we can use the calculations above and see how they match to the time spans given by radiocarbon dates. This will allow inferences to be made about the differences between layer 8 and the other layers and also how the accumulation rates based on seasonality data compare to rates based on radiocarbon dates.

Using the minimum and maximum periods of accumulation for layer 8 (3 and 9 months, respectively), we extrapolate the accumulated volumes per year. A short period of 3 months results in a high accumulation rate of 2.5 $m^3$/year, while a long period of 9 months results in only 0.8 $m^3$/year.

Applying these rates to the overall volume of JW1727 (163 $m^3$), we estimated the years of constant shellfish exploitation and accumulation that it would take to create the mound. Using a slow accumulation rate of 0.8 $m^3$/year (based on 9 months), it would take 204 years. Using a high accumulation rate of 2.5 $m^3$/year (based on 3 months), it would take only 65 years. Compared to the ages based on radiocarbon dates (16 years, 65 % probability and 88 years, 95 % probability), the high accumulation rate of 2.5 $m^3$/year is much more likely (Fig. 8).

This overlap of estimated ages is a positive indication that accumulation rates derived from seasonality data can be a rough estimate for shell accumulation. It also suggests that layer 8 is not the only layer that accumulated rapidly (within months) because the higher end of accumulation rate that is likely for layer 8 (2.5 $m^3$/year) provides a much better fit with the overall midden and thus the average accumulation rate for every other layer that was sampled in this study. Reasons for why the other layers do not show this in the seasonal distribution are discussed below (5.5).

The main uncertainty in this comparison is the fact that in summer, the $\delta^{18}O$ values are very constant, making it difficult to accurately pinpoint the number of months of deposition and derive an accurate accumulation rate. Also, it would have been more desirable to have had more than one layer that permitted the estimation of accumulation

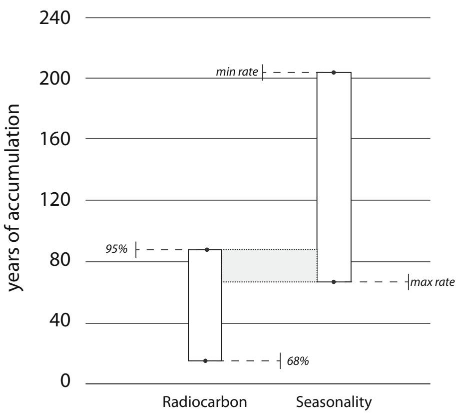


**Fig. 8** Box plots of estimated shell accumulation in years based on radiocarbon dates and seasonality data. Note the overlap at 65–88 years (*grey area*)

rates. This is especially true, given the high rate of accumulation indicated by the radiocarbon dates.

## How Normal Are Anomalies?

A prerequisite for our study is stratigraphic information about the sample origin. This concept is similar to the interpretation of radiocarbon dates using Bayesian modelling, where, aside from the source of the date, the stratigraphic context can significantly contribute to the interpretation of the result (Bayliss 2015; Buck and Meson 2015).

In many seasonality studies, detailed stratigraphic context is often not reported because a general interpretation of the seasonality of the site as a whole is being sought (Burchell *et al.* 2013; Culleton *et al.* 2009; see also Thomas 2015). Because the stratigraphic context is not reported and the seasons of exploitation are presented in bulk, it is possible that accumulation episodes with very distinct seasons of exploitation, each of which is happening in different periods of the year, have been amalgamated, giving a false impression of year-round exploitation.

The approach used by Thompson and Andrus (2011) can help to resolve or at least partially disentangle these problems because the shells and their seasonal signal can be grouped by layer or even position within the layer.

Regardless of stratigraphic information, most layers within JW1727 do not show any signs of grouped shells with the same season, and it is uncertain as to why layer 8 is different from the other layers. At Culverwell (Mannino and Thomas 2001) and Sapelo island (Thompson and Andrus 2011), exploitation intensity and rapid accumulation was suggested as the main driver for the grouping of seasonality values. Furthermore, at Sapelo Island, non-grouped seasons were used to rule out a rapid accumulation in other layers.

At JW1727, we find layers with mixed and with grouped seasons. However, the accumulation rate based on radiocarbon dates suggests that each layer had to accumulate equally rapid as layer 8. This raises the question of whether exploitation intensity or feasting was the main reason that the seasonality values in layer 8 are grouped. Instead, it suggests that these special layers are simply the only ones to have a preserved succession of seasons.

An explanation is that formation processes have prevented us from taking sequential samples from top to bottom of each layer. It is possible that although the layers were undisturbed, they were sectioned in an ‘inconvenient’ location during the excavation, where the exposed section was in fact not the centre of the shell deposit but its rim. By sampling shells from the assumed ‘base’ of the layer, we could have actually sampled rims of different seasons because the excavated section unknowingly cut the layers at different places (Fig. 9a). Additionally, the ‘centre’ of each deposition can vary spatially as people changed their processing and discard practices. Considering these influences, it is quite 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 enabled us to capture a linear sequence through the shells deposited in that particular layer. Even here, we were not able to capture individual accumulation episodes but found a mix of two adjoined seasons (Fig. 9b).

Considering that the supposed differences in accumulation rates mainly depend on visibility, and considering that evidence for feasting is often defined as an unusually

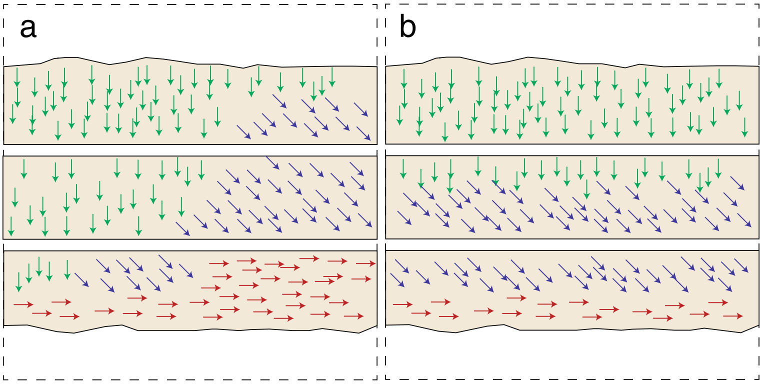


**Fig. 9** Theoretical distribution of seasonality values. **a** Layer with multiple centres of depositions or inconveniently sectioned during excavation. **b** Layer with successive order of seasons aligned with the stratigraphic sequence, similar to the three spits within layer 8 of JW1727

large and dense concentration of food remains (*e.g.* Hayden 2001; Twiss 2008), it is necessary to re-evaluate the use of seasonality data as evidence for feasting. The different results of seasonality data could falsely imply that some layers (layer 8 in our case or Ring I in Thompson and Andrus 2011) may be the result of feasting, when in fact they simply may have been excavated or sampled in a way that makes it possible to see them as having accumulated more quickly than other layers, which are disturbed or sectioned inconveniently (*i.e.* an artefact of sampling). Judging by the short time span indicated by radiocarbon dates of JW1727, this is likely the case for the other layers that were sampled for seasonality (13, 18 and 20). This problem will persist until the development of more comprehensive datasets for seasonality data, which allow us to accurately map the seasonality throughout the layer in three dimensions. In turn, this will provide an assessment of how the layers are preserved, of intra-site variability of accumulation rates, and allow the most in-depth assessment yet of formation processes in shell mounds.

## Conclusion

Radiocarbon dates and seasonality data both indicate a rapid accumulation of *C. fasciatus* deposits. Within the mound, these accumulations were most prevalent in layer 8, where individual spits gradually changed their seasonal signal in agreement with their stratigraphic sequence. These results made it possible to assess the accumulation rate in one part of the midden at a previously unknown resolution for shell midden deposits.

However, we need to acknowledge and better understand the formative and post-depositional complexity of the archaeological deposits. The fact that some layers allow us to trace the accumulation of shells during one specific episode of occupation is an interesting observation and it opens up a new line 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 consumed during these few months? Was this the only site that was visited 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? These are questions that may be answered at other sites where archaeological artefacts and human remains are more abundant than on Farasan.

Finding layers in ideal stratigraphic conditions is not straightforward, and no guaranteed method is currently feasible unless we increase the amount of shells sampled to hundreds or thousands of shells per layer. Recent advances in rapid production of seasonality data suggest that this is feasible in the future with the development of new methods (García-Escárzaga *et al.* 2015). Until then, it is worth recording the stratigraphic information in combination with seasonality samples to avoid possible biases as well as find traces of rapid accumulation.

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