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Beyond consumption and discard: A comparative sedimentological analysis of two shell deposits from Albatross Bay, Australia, and the Farasan Islands, Saudi Arabia

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Abstract

We use a sedimentological approach to examine the formation and deformation processes associated with the accumulation of shell deposits in two major clusters of shell mounds, the Weipa group in the monsoonal environment of Albatross Bay in the Cape York Peninsula of northern Queensland, Australia, and the Farasan Islands group in the semi-arid environment of the southern Red Sea sector of Saudi Arabia. The comparison of such disparate case studies is deliberate, intended to highlight generic issues of shell accumulation and degradation irrespective of the taxonomic composition of the shells or cultural and environmental histories. It also reflects recent fieldwork in both regions conducted in parallel with collaborative arrangements for sharing of ideas and approaches and exchange of personnel in order to establish a common baseline for comparison. Comparative analysis of shell composition, fragmentation, and accumulation highlights similarities despite the different cultural and environmental contexts of the two case studies. These similarities suggest that the size and form of shell deposits are altered by a combination of processes reflecting ongoing changes in deposit composition unrelated to human actions of shell discard. Even where large shell deposits are visible and available for sampling, what is preserved is neither a static reflection of initial deposition nor of undisturbed or “completed” form. We consider the influence of such processes on assessments of rates of deposition and the interpretation of variations in the shape and size of shell deposits.

Key words

Shell mounds, formation, fragmentation, accumulation rate, Farasan, Red Sea, Cape York

1 Introduction

The archaeological significance of coastal resources, often with emphasis on marine molluscs and shell middens, features in a number of discussions of human biological and social change including early human development and dispersal (e.g., Stewart, 2010; Groucutt et al., 2015; O'Connell and Allen, 2015; Kyriacou et al., 2016; Will et al., 2019), and later developments in economic intensification, population increase, increased sedentism, and cultural complexity (e.g., Erlandson 2001; Bailey and Milner, 2002; Balbo et al. 2011; Bailey et al. 2013a; Jerardino, 2012; Marean, 2014, Roksandic et al., 2014). In most of these studies, highly visible accumulations of shell remains (often termed shell mounds, e.g., Stein, 1980; Bailey, 1994; Marquardt, 2010; Villagran et al., 2011; Saunders, 2017, and hereafter referred to as shell deposits) are an important source of information. Differences in the form, size, and composition of these deposits are typically interpreted in terms of human shellfish predation, consumption, and shell discard, and in some cases in terms of mortuary or ceremonial activity. Studies of socio-economic intensification (*sensu* Morgan, 2015), for example, use the size of deposits in the form of absolute measurements of shell deposit thickness combined with depth measurements of radiometrically dated samples to produce accumulation rates linked directly to intensification processes whether these are economic (i.e., how much consumption and discard occurred within a given time frame, e.g., Letham et al., 2017), or social (i.e., how many people came together in a particular location, e.g., Morrison, 2013b).

The issue with such behavioural interpretations involves the many variables besides human behaviour that affect shell deposits. For example, global sea level changes have restricted the places where shell deposits are visible, with many pre-mid-Holocene records now under water (Erlandson, 2001; Bailey and Milner, 2002). Nevertheless, large shell deposits exist in a number of places worldwide, so here we focus on the importance of variables that affect shell deposit composition, building on studies of deposit alteration over time through the action of mechanical and chemical processes like fragmentation and dissolution (e.g., Muckle, 1985; Sullivan, 1993; Shiner et al., 2013; Villareal, 2015; Fanning et al., 2018).

We consider the formation and preservation of coastal archaeological deposits, focusing on case studies from two places where a substantial coastal shell deposit record developed during the Holocene: Albatross Bay in northern Cape York, Australia, and the Farasan Islands in the Red Sea, Saudi Arabia. We apply a comparative, sedimentological analysis to these deposits located in places with different geological and culture histories to determine how various biotic and abiotic processes, in addition to the act of shell discard by humans, contributed to shell deposit formation and deformation through time.

The comparative research design using shell deposits from two culturally unrelated regions is therefore intended to inform on the challenges posed by studies of deposit formation when assessing the behavioural interpretations of shell deposits more generally. It has long been recognised that coastal shell middens facilitate comparative analyses from different parts of the world because of the general similarities in their form, composition, and modes of accumulation, the general behaviour and ecology of the marine molluscs, and the relatively simple methods involved in their collection and processing (Bailey and Parkington, 1988; Bailey et al., 2013a; Roksandic et al., 2014). However, examples of long-range comparative analysis and interpretation conducted within the same framework of objectives, field sampling and analytical methods are rare. In the study presented here, comparison has been facilitated by two major projects that began at about the same time. Both projects focused on the application of multiple radiocarbon determinations to significant concentrations of shell mounds in different parts of the world. In each region, the shell deposits are dominated by a single mollusc taxon, and show a wide variation in size, ranging from shell scatters to mounds many metres thick. Inter-project collaboration began at an early stage to develop similar standards of sampling and dating, with exchange of personnel and joint experience of field conditions in both regions.

2 Interpreting Shell Deposits

Ethnographic descriptions as well as archaeological studies describe the discard of large numbers of whole valves in mounded shell deposits (e.g., Bailey, 1977; Faulkner, 2010; Rowley-Conwy, 2013; Sall, 2013). These studies often report shell processing with little macroscopic damage or mechanical breakage. Bivalves are opened easily using a sharp thin blade or through application of heat at low temperatures (Aldeias et al., 2019). Meat removal from some gastropods may also occur without damage to shell dimensions, for example by perforation near the apex to cut the adductor muscle or breaking the aperture to facilitate rapid meat removal (Oxenford et al., 2007). Therefore, if complete shells of one species are recoverable from a deposit, counting these shells should provide estimates of the numbers of shellfish consumed, and dating should show how these numbers may have changed through time. However, despite the ease of processing, shell breakage often occurs after deposition through a variety of mechanisms. As shell morphology and minerology is variable even within a genus, morphological differences between shellfish taxa (i.e., microstructure, shape, size, thickness, and type of sculpture present), are likely to influence their level of post-depositional breakage (Claassen, 1998). Part of the reason relates to the physical structure of shells and their volume. How much of the shell deposit they form depends on a combination of this volume and their numbers (and as we illustrate below, their state of preservation). A high volume with very abundant shell from one species will reduce the ability to detect other species within a given volume of excavated deposit. All deposits have components that accumulate at different rates, and in this sense, shell-deposits are no different from others. However, it is also true that few other types of archaeological deposit have components with markedly different volumes that may change over time.

This has implications for the nature of time averaging in this deposit type. In many types of archaeological deposit, artefact deposition is much faster than the rate of sediment deposition. While there are certainly instances where sediment accumulation can occur at rates higher than the rate of artefact accumulation, in shell deposits where, as the name suggests, shell forms the bulk of the clasts, the accumulation of these shells is likely to occur much more quickly than the rate of deposition of the majority of other artefacts or faunal remains. Additionally, the space that shell clasts occupy is liable to change through time due to processes like fragmentation. Therefore, volume becomes time or energy dependent, complicating the calculation of rates of deposition and therefore interpretations that rely on these data (Holdaway et al., 2017). As we show in the case studies below, shell deposits may also act as sediment traps, producing their own microenvironments that attract, for example, vegetation. This in turn promotes sediment deposition and movement through the deposit, further affecting rate calculations and indeed deposit composition and shape. As a consequence, the form, size, and composition of shell deposits may continually change through time.

Palaeoeconomic measures related, for example, to socio-economic intensification often rely on calculations of meat yield (*sensu* Robins and Stock, 1990, p. 81) together with metrics such as vertical or volumetric accumulation of a deposit (e.g., Hausmann and

Meredith-Williams, 2016; Garvey, 2017). Here we consider how taphonomic processes outside of human shellfish collection and discard contribute to processes of deposit formation and deformation. Using case studies from markedly different environments, we illustrate how the modern appearance of shell deposits is not solely the result of shell clast accumulation but requires in addition an understanding of the influence of other sedimentary inputs related to local environmental processes that occur during and after deposit formation. Given the importance of these inputs, the archaeological challenge is to consider how they may influence behavioural inferences based on the size, form, and accumulation-rate of shell deposits.

3 Case Studies

3.1 Albatross Bay, Australia

This region is a tropical monsoon environment with marked seasonal shifts between a wet season and a dry season, and four major river estuaries that drain into the bay with extensive intertidal mudflats, belts of mangrove vegetation, and supratidal mudflats subject to periodic inundation during the wet season (Fig. 1). There are at least 500 shell deposits, the largest forming mounds as much as 10 m in height, which form clusters along these estuaries, and their archaeological investigation spans more than 50 years (Wright, 1971; Bailey, 1975, 1977, 1994, 1996, 1999; Stone, 1992, 1995; Bailey et al., 1994; Morrison, 2010, 2013a, 2013b; Shiner et al., 2013; Holdaway et al., 2017; Larsen et al., 2017). They are often referred to collectively as the Weipa shell mounds, named after the peninsula where the modern settlements are located. The deposits formed predominantly through the accumulation of *Tegillarca granosa* (Linneaus, 1758) valves, also known as *Anadara granosa* (Huber, 2010). As in other parts of the world, behavioural and cultural interpretations of these deposits have predominated, with less attention to their formation histories.

Our Albatross Bay case study comes from the results of a multi-disciplinary research project concentrating on one small region, Wathayn, near Weipa on the Embley River. A total of 158 shell deposits were identified in the Wathayn study area (Holdaway et al., 2017; Larsen et al., 2017) along approximately 4 km of the northern side of the Embley River, and within 1200 m of the present coastline. The shell deposits range from low density shell “scatters” to shell “mounds” up to 2.35 m high. Shell deposits occur on muddy estuarine floodplains, low sand or gravel beach ridges and laterite slopes, and ridges at the edge of the floodplain up to 10 m above present mean sea level (PMSL).

According to Oon (2018), the 6445±45 cal BP sea level in Albatross Bay was −1.7 m PMSL. Sea level rose until approximately 4000 BP reaching +1±0.5 m PMSL. At Kwamter, downstream from Wathayn (Fig. 1), supratidal mudflats formed where space allowed. Mangrove forest formation kept pace with sea-level rise until it reached PMSL and above, when intertidal mudflat formation at Kwamter suggests an open shoreline perhaps free of mangroves. During this sea level high stand, to the east of the Wathayn shell deposits, a beach ridge began forming sometime before 4000±325 cal BP continuing until at least 3153±319 cal BP (Oon, 2018, p. 227). From 2200 cal BP to present, sea level fall increased the accommodation space available for sedimentation at the coast. This fall was coincident with an increase in effective precipitation (Stevenson et al., 2015) providing more sediment to the coast, infilling the river channel and allowing mangroves to re-establish (Oon, 2018, p. 245). The sandy mud sediments deposited in Wathayn and Kwamter, and including the modern supratidal mudflat, have a mean grain size of approximately 18.7 µm with 76% silt and clay with a high organic content (10%) (Oon, 2018). According to previous analyses of productive *T. granosa* populations from Malaysia and India, *T. granosa* animals prefer sediments with high proportions of silt and clay (<124 µm), a slope of 5–15 degrees, salinity of approximately 26–31 ppt (with a range of tolerance between 5–36 ppt) and high organic content when located in the intertidal-subtidal zone (Pathansali, 1966; Narasimham 1980; Broom, 1985; Tiensongrusmee and Pontjoprawiro, 1988).

At Wathayn, Fanning et al. (2018) demonstrated that beach ridges ceased formation around 4710 cal BP, with radiocarbon determinations on shells from the base of the oldest shell deposit dating to around 4000 cal BP (*T. granosa* valve from WP-SM55, Wk-35218 reported in Holdaway et al., 2017). Numerous shell deposits in Wathayn have dates in the range 2500–2000 cal BP with some deposits dating before and after this period.

3.2 Farasan Islands

The Farasan archipelago is in a semi-arid environment and lies offshore of the south-west coast of Saudi Arabia in the southern Red Sea. It comprises over 120 islands dominated by the three largest islands, Farasan al Kabir, Sajid, and Qummah, all of which have large numbers of shell mounds (Fig. 2). Until 2006, these sites were unknown to the wider world. Since then the DISPERSE project has mapped over 3000 shell mounds ranging in thickness from less than 1 m to over 5 m, often forming clusters around shallow bays, and conducted excavations at 19 of them (Bailey et al., 2013a, 2013b; Meredith-Williams et al., 2014, 2018). Radiocarbon determinations indicate that most of the shell material accumulated between 7400 and 4700 cal BP (Hausmann et al., 2019). The dominant taxon throughout is the small gastropod *Conomurex fasciatus* (Born, 1778), although other taxa are also quite common and occasionally dominate in individual layers.

The islands comprise cemented coral reef ‘limestone’ that has been uplifted and deformed by a combination of basin-wide rifting and sea-floor spreading of the Red Sea, and more localised diapirism of Miocene evaporites (thick beds of salt), which have locally risen to form salt domes associated with deep circular basins offshore (Purser and Bosence, 1998; Bantan, 1999; Inglis et al., 2019; Sakellariou et al., 2019). The land surface is dominated by cemented coral platforms with variations in relief created by minor tectonic faulting and folding and a maximum elevation of approximately 75 m asl, patchy distribution of soils and sediments, and limited surface water and vegetation cover for most of the year (Bailey et al., 2013b; Pavlopoulos et al., 2018). Modelling of sea-level change to take account of tectonic and isostatic movements shows that in the Holocene, sea level rise at Al Birk in the southern Red Sea reached PMSL by approximately 7000 BP with a 3.8 m high stand at 6300 BP (Lambeck et al., 2011). Due to the variability of tectonic warping across the archipelago, the coastline lacks a consistent elevation, with some shell mounds at or close to the present sea level and others on coral terraces uplifted by as much as 6 m and undercut by marine erosion (Hausmann et al., 2019). Some of the largest concentrations of shell deposits including most of the large mounds are located on palaeoshorelines around large shallow bays that once formed marine inlets; these are now dry sand-filled basins because of tectonic uplift, infilling with wind-blown sand or a combination of both processes.

4 Methods

4.1 Field Recording and Sampling

To expose the internal stratigraphy and obtain samples from the shell deposits at Wathayn, trenches 1 m wide were excavated by hand along the short axis of each shell deposit, starting at the outside where the deposit intersects the surrounding terrain and working systematically to the centre (Fig. 3) (Fanning et al., 2018). After completing descriptions, surveying, and sampling, trenches were backfilled using the stockpiled material, in accordance with excavation protocols agreed to by the indigenous Traditional Owners. A column sampling technique provided samples from trench end walls (Treganza and Cook, 1948; Shiner et al., 2013, p. 72). Contiguous spits measuring 20 cm wide, 20 cm deep, and 10 cm thick (maximum volume 4000 cm^3) were excavated using trowels and brushes from the surface down to the substrate beneath the deposit. All the material from each excavation spit was placed in bags and labelled with a unique sample identification number. A description of sediment texture, structure, fabric, degree of compaction, shell and other organic content, other inclusions, concretions, and colour was recorded. The depth of each excavation spit below the deposit surface was recorded using a Total Station.

The analyses reported here are from a column from one deposit, WP-SM72 (Fig. 4). WP-SM72 is one metre deep, with an area of 260 m^2, a volume of approximately 107 m^3. It is sitting on a substrate of brown sandy silt with sub-rounded ironstone gravel inclusions and absence of shells and is approximately 400 m from the modern Embley River shoreline. The pre-deposit landform is 4.09 m APSL, and approximately 200–300 m distant from the past coastline at the time when shells began to be accumulated (3000–2000 cal BP). Calibrated radiocarbon determinations on *T. granosa* valves from the deposit span 10–100 years, from 2616±62 (Wk-32310) to 2606±25 cal BP (Wk-32308) (see Holdaway et al., 2017 for calibration methods and Delta R correction information).

At Farasan, trenches of 1 m width, or 2 m width in the case of taller mounds, were excavated from the edge to the centre of each deposit along the shortest axis. As at Wathayn, trenches were backfilled with the stockpiled material after completion of the sampling and description. Arbitrary spits, each measuring 20 cm x 20 cm x 5 cm, were excavated as a vertical column through the end wall at the centre of the deposit and into the pre-deposit substrate where possible. Where excavation of a spit encountered a change in sedimentary composition (generally coincident with a visible change in the composition of the deposits such as a layer of ash, or a change in shellfish condition or taxonomic proportions) sample collection ceased, and a new spit was initiated along the stratigraphic boundary. All sedimentary material was removed, bagged, and labelled with a unique sample identification number. Stratigraphic sections were drawn by hand and descriptions of each stratigraphic layer were made. Shell and charcoal samples were collected from the end wall of the deposit and submitted for radiocarbon dating. Radiocarbon ages were calibrated using the Marine13 calibration curve (Reimer et al., 2013) using Oxcal 4.3 (Bronk Ramsey, 2009) and a Delta R correction of 188±44 following Hausmann et al. (2019).

The analyses described here are from the end-wall column (depth 48 cm) of one deposit (JW1705) from Janaba West, a large inlet at the western end of Janaba Bay (Fig. 5). JW1705 is a low shell mound with a maximum thickness of 1.1 m, an area of 287 m^2 and an estimated volume of 69 m^3. It is situated on a cemented coral surface 840 m inland of the modern coastline. It is positioned 20 m inland from a beach ridge on which many other shell mounds are located. Previous research shows that this formed the shoreline at the edge of a shallow bay at the time when the sites located on it were in use (Alsharekh et al., 2014; Meredith-Williams et al., 2018). Three radiocarbon determinations on marine shell from JW1705 indicate that shell was deposited at this location over a span of about 4200 years, from before the high sea-level stand created the nearby palaeoshoreline and continuing in use after the sea had retreated from that palaeoshoreline. The earliest radiocarbon determination is from near the base of the end wall section (7210±66 cal BP, OxA-31167) and the youngest from near the surface of the side wall (3033±81 cal BP (OxA-31168) (Fig. 6) (calibrated in Oxcal using Intcal20 and the Delta R correction in Hausmann et al. 2019). How these dates relate to human action will be examined below.

Both sites are relatively small in terms of thickness and volume compared to the total size range of deposits in each case-study region and were selected for that reason, in order to provide a manageable quantity of material for a pilot study given the time and resources available, while also tracking variation through the full depth of the deposit in each case. It is also pertinent to note that both deposits are located some distance inland from their contemporaneous shorelines in contrast to other shell deposits in each group which are located on or closer to their respective shorelines.

The column sampling technique differs slightly for each location. Although the samples have the same length and width dimensions, the Wathayn samples cross visually assigned stratigraphic boundaries, whereas the Janaba West samples do not. At Wathayn, stratigraphic boundaries were very blurred and difficult to assign to depositional episodes, with variation throughout the section appearing to be taphonomic or post-depositional rather than related to events of human discard behaviour. Species proportions were not a useful indicator as previous research demonstrated these deposits were predominantly composed of one species of shellfish (e.g., Bailey, 1975; Morrison, 2010; Shiner et al., 2013). The stratigraphic profile for Wathayn therefore represents the "lithographic" profile (Stein, 1992, p. 74). Sampling crosses defined lithographic boundaries as these could not be linked to human discard behaviour. At Janaba West, the sampled portion of the stratigraphy in the centre of the deposit showed layers definable from visual estimates of species proportions. According to Stein (1992, p. 74), both the case studies conform to sampling the "biostratigraphic unit" (as chronology was not known at time of sampling) characterized by a visual assessment of their macro-biological contents. To make samples comparable, the results are reported as a percentage of the total sample value, rather than as measured weights. The results demonstrate how deposit composition varies with depth within biostratigraphic layers regardless of which technique is used.

4.2 Laboratory Analyses

The sedimentological approach used in the analysis is based on standard techniques applied to geological sediments, modified to protect the fragile shell material. Shell and non-shell components are similarly treated, and separate components of each sample are expressed as a proportion of the total sample weight or volume. By adopting this approach, assessment of the contribution made by other formation and deformation processes is made possible, in addition to shell discard. Samples were analysed at the University of Auckland, New Zealand, in the case of WP-SM72, and at the University of York, United Kingdom, in the case of JW1705.

Soil micromorphological analysis based on analysis of thin sections of small bulk samples recovered intact from undisturbed deposits has also been applied to shell deposits with some success (Villagran, 2014, 2019). We were not able to use that technique in this study because many of the deposits we are dealing with are too loosely structured, often with large shell clasts and voids, to permit the removal of intact block samples without disturbance or loss of material, and the technique could not be applied consistently throughout the full depth of deposits selected for sampling.

In the laboratory, each sample bag was weighed, and its contents hand sieved through a 1 mm test sieve with square apertures for one minute to remove fines. This required multiple passes for each bag to ensure as much fine material passed through the screen as possible while avoiding binding. All fines were captured in a pan. Both the large and <1 mm size fractions were weighed, and the fines bagged. Where fine sediment adhered to the clasts after sieving, the >1 mm fraction was washed while resting on a 1 mm sieve. The washed material was air dried on trays for at least 48 hours, or with the use of a drying oven (temperature 30–40° C). Most standardized procedures using nested test sieves recommend a mechanical shaker for at least 10–20 minutes to ensure reliable measurements of particle size (e.g., ASTM D6913; Folk, 1974). However, as many components were small and fragile, the sieving procedure was modified to prevent their fragmentation. Consequently, large rocks were removed prior to sieving.

Next, the entire large size fraction was passed through a set of nested test sieves at half phi intervals (the logarithmic transformation of millimetres) to −3 Φ (8 mm) (Krumbein, 1934). Large elliptical clasts of non-spherical form (such as bivalve valves that are long and flat) do not reliably orient themselves perpendicular to square apertures during sieving (Ludwik and Henderson, 1968; Matthews, 1991). Therefore, to obtain rapid and repeatable measurements of the shortest diameter of each clast, all objects >8 mm (including previously removed rocks) were manually passed through apertures by hand at any orientation to the aperture, either through nested sieves or through a Perspex template (with apertures up to −6.5Φ, 90 mm). No sampled material exceeded 90 mm. Due to their irregular shape, it is possible for shell clasts to pass through the aperture on the diagonal. This means that larger clasts than anticipated may get captured on the sieve. For example, a mesh screen with square apertures 31.5 mm in width can pass thin flat clasts across the diagonal as wide as 44.55 mm. This skewed results towards the finer classes (Matthews, 1991, p. 25).

All material falling through the 8 mm sieve was collected in a pan and weighed. If this portion weighed more than 100 g, it was quarter subsampled using an Endecotts sample splitter with 12.7 mm (1/2 inch) sized openings, to systematically reduce the amount of fine material to be sorted. If the captured material was less than 100 g, this splitting phase was omitted. All material finer than 8 mm was then hand sieved for one minute through another series of nested sieves at half phi intervals to 1 mm. Each sieve stack was 2–3 sieves high to allow adequate horizontal and vertical agitation of particles. Unconsolidated and weakly consolidated sediment was separated by pressing between a finger and the surface of the tray or using a mortar and rubber pestle. No attempt was made to disaggregate cemented sediments as rock clasts were predominantly located within the pre-deposit substrate and determining their grain size was not considered necessary for analysis.

Hand sorting and sieving sediment divided each sample into 14 size interval categories from 90 mm to 1 mm. The sediment was then sorted into its various components, weighed, and bagged. The components identified were whole and fragmented molluscan valves, rocks, charred and uncharred organic material (twigs, insect carapaces, roots, and leaf litter), teeth, coral, encrustations (calcium carbonate precipitate produced by marine organisms), exoskeletons (i.e., of crustaceans), bone, foraminifera tests, and the spines and stems of echinoderms. The term “valve” is used in preference to the word “shell” to describe the piece/s that originally housed bivalves and gastropods. The term distinguishes between the entire shell exoskeleton (as found in live molluscs) and other components that occur in Farasan shell deposits such as the radula of *Conus* sp. or opercula of *Nerita* sp. The word “valve” does not only apply to bivalves, as most gastropods are considered univalves (i.e., having one valve) (Claassen, 1998). In some cases, gastropods can also be bivalved (e.g., those from the family Juliidae, E. A. Smith, 1885). Therefore, it was important to be able to categorise each component with as little ambiguity as possible. Components were sorted by eye to 2 mm. Material 2 mm and smaller was sorted by hand using a low-powered microscope (1.5–2 x magnification). Despite recommendations against the use of shell weight by some scholars (e.g., Claassen, 1998), García (2008) suggests that weight values can be useful for determining shell composition throughout a deposit. Additionally, where shells are highly fragmented with many clasts, measurement of shell weight is suitable and practical (Hammond, 2014). Identification to the most specific taxonomic rank was applied to all whole valves in fractions down to the 1 mm sieve. Taxonomic identification for the Wathayn deposit used Lamprell and Healy (1998), Huber (2010), and Stanisic et al. (2010), while classification for the Janaba West deposit followed Oliver et al. (1992), Rusmore-Villaume (2008), Zuschin and Oliver (2003), Zuschin et al. (2009), Huber (2010), and Janssen et al. (2011). Species were cross checked using the World Register of Marine Species (WoRMS) online database (WoRMS Editorial Board, 2019). Taxonomic identification was only attempted for shell fragments within the Udden (1914) and Wentworth (1922) gravel size fraction (≥2 mm) as fragments passing through the 2 mm mesh and beyond had lost too many landmarks to make shellfish species identifiable.

In order to obtain the correct value of each component as a proportion of the whole sample (as each subsample never amounted to a perfect quarter), each component within the subsample (including material captured in the pan) was multiplied by their "splitting factor" (Folk, 1974, p. 33). This is given by the total weight of material prior to sieving (measuring less than 8 mm) divided by the weight of the subsample split that was sieved. Material <1 mm captured in the pan was mathematically added to the fine material removed prior to analysis to gain a correct value for unanalysed fines for each sample. Sample data were entered into the GradiStat (v8) grain size distribution package for Microsoft Excel (Blott and Pye, 2001). Sample statistics reported here follow the Folk and Ward (1957) method; however, sample type, textural group, and sediment names follow Blott and Pye (2001), as additional gravel size categories are useful in these circumstances for distinguishing differences in gravel-sized particles.

5 Results

5.1 Shell deposit composition

*5.1.1 Case Study One: WP-*SM72*, Wathayn*

The column excavated at WP-SM72 weighs 46.89 kg in total. In addition to the whole and fragmented molluscan bioclasts that comprise 57.06% of the deposit (ranging from 22.42–9.05% of each spit by weight), there are a small number of broken and intact exoskeletons of crustaceans (*Balanus* sp., 0.39%) (Fig. 7). WP-SM72 also contains a large amount of sedimentary material finer than 1 mm in size (39.98%). Other solids present include rocks (2.06%), as well as charred (0.48%) and uncharred organic material (0.03%). Organic material includes leaf litter, twigs, seeds, roots, and insect chitinous exoskeletons (predominantly head capsules). Uncharred organics are prevalent in the first 10 cm of deposit reducing to <2 g per spit for the remainder of the deposit. In contrast, charred organic material (predominantly macroscopic burnt wood) rises and falls throughout the sequence with a peak at 50–60 cm depth. Rock weight drops from nearly 150 g at 0–10 cm depth to approximately 13 g between 30–50 cm depth then steadily rises to its peak of around 300 g at the base of the deposit (90–100 cm).

Taxonomic identification to species was possible for nine molluscs. Other specimens were categorized to higher taxonomic divisions where appropriate (Fig. 8). One bivalve species, *T. granosa* (mean length of modern adult specimens 38.46±11.94 mm, Faulkner, 2010), dominates the proportions of shell clasts (87.07% by weight). The second largest proportion of shell material from this deposit comes from the “unidentified” category, which comprises all unidentifiable calcareous material (9.65%). The third category, represented in increasing amounts towards the base of the deposit, is a venerid bivalve, *Marcia hiantina* (1.59%). The remaining taxa (1.69%) include gastropods (Cerithiidae, *Cerithium* sp. Eulimidae, *Ellobium* sp., *Nerita balteata, Nerita* sp., and *Telescopium telescopium*), bivalves (*Atactodea striata, Geloina expansa* (1%), *Saccostrea cucullata* (0.45%), Ostereoidea, *Placamum lamellosum,* and Veneridae), and terrestrial gastropods (*Trachiopsis setosa*, Camaenidae, and Helicarionidae).

5.1.2. Case Study Two: JW1705, Janaba West

The analysed column contains 16.72 kg of sediment of which 32.91% is calcareous solids produced by marine organisms (Fig. 9). This proportion includes whole and fragmented mollusc valves, coral, crustacean and echinoid exoskeletons, foraminifera tests, and loose encrustations. Over half of all sediment is finer than 1 mm (64.32%). Other components include non-human bone (0.01%) and non-human teeth (<0.01%), charred and uncharred organic material (i.e., fine roots, <0.01%), and rock clasts (i.e., quartzose sand and breccia, 2.76%).

In contrast to the Weipa deposit, JW1705 contains a greater taxonomic diversity. Calcareous solids produced by marine organisms are identified to five Phyla (Arthropoda, Mollusca, Echinodermata, Foraminifera, and Cnidaria), with molluscs contributing 99.11% by weight. Other solids (0.84%) present include exoskeletons from crustaceans (i.e., *Cranuca inversa* and *Balanus* sp.) and echinoderms, coral (Cnidaria), and foraminifera tests (i.e., *Sorites orbiculus* and *Peneroplis planatus*). The remaining calcareous material (0.05%) is comprised of encrustations. These are generated by aquatic organisms that bind sedimentary particles to adhere to various substrates creating a shelter or a living framework such as polychaetes, coralline algae, foraminifera, corals, bivalves, bryozoans, and others (Wust, 2011).

Considering Mollusca alone, gastropods contribute 82.03% and bivalves 1.06% with the remaining 16.91% of objects unidentifiable. Twenty-nine families of molluscs are identified, with 19 molluscs identifiable to species level. Six taxonomic groups by proportion dominate, accounting for 96.48% of all molluscan clasts within the column (Fig. 10). The remaining 3.52%, grouped here as “Other”, consists of a further 46 identified taxonomic categories of varied rank. Like the Wathayn deposit, there is a single dominant species, *Conomurex fasciatus,* a small herbivorous conch (length of adults 25–50 mm, Hausmann et al., 2017) comprising 71.76% molluscan solids by weight. Another similarity is that the second largest proportion of molluscan solids are unidentifiable fragmented valves (16.91%). *Chicoreus* sp., a genus of large carnivorous gastropods (maximum shell length of *Chicoreus ramosus* approximately 33 cm, Poutiers, 1998; Worms Editorial Board, 2019) comprises the third largest grouping (2.83%).

5.1.3. Summary

The graphs for both the Wathayn (Fig. 7) and Janaba West (Fig. 9) columns indicate that fines <1 mm and rocks make up a large proportion of the sediment. In the Wathayn deposit, this constitutes 39.98% of the column. Within the Janaba West column, it accounts for 67.08%. In both examples, the distribution of components is similar with an increase in the fine sediment and rock proportions seen at the top and bottom of the column, and with rock clasts increasing towards the base. From these proportions, and despite the outward appearance of both mounded features as comprised largely of shells, their composition instead indicates formation from more than one sediment source and more than one process, that is, not human discard of shells alone. In a sense, both examples present as archaeological sediments (Goldberg and McPhail, 2006, p. 27) rather than as shell mounds.

5.2 Particle size and fragmentation of shell clasts

5.2.1 Case Study One: WP-SM72, Wathayn

The ratio of fragmented to whole molluscan clasts for WP-SM72 shows four peaks in fragmentation (Fig. 11). The first peak is within 10 cm of the surface, the second peak is at 30–40 cm, a small peak exists at 60–70 cm, and a drop and then a spike occurs at 80–90 cm increasing to complete fragmentation of all clasts in the basal 10 cm (90–100 cm). This pattern is interpreted to reflect repeated accumulation and breakage throughout the deposit. Except for the basal layer, those layers exhibiting higher numbers of fragmented valves lie above layers with proportionally higher numbers of whole shells and reflect at least four periods of exposure to processes leading to shell fragmentation. At the base of the deposit, whole shells were deposited and completely fragmented by mechanical processes such as trampling by people or animals before further shell deposition occurred. The fragments at this lowest level are quite large compared to the rest of the deposit, suggesting there was some protection of the clasts, perhaps by the presence of a permeable substrate upon which the first shell deposition occurred. Muckle (1985) reports a similar pattern, with an increase in fragment size resulting from trampling by a human agent on a loam substrate when compared to a pre-existing shell bed. Findings from *T. granosa* dominated deposits at Blue Mud Bay (Faulkner, 2010) and Beagle Gulf in Northern Australia (Bourke, 2004) also showed that valves located in the centre of the deposit are comparatively more protected from fragmentation processes than those from the base or surface of the deposit.

As the deposit accreted, more valves were preserved intact, until the top 20 cm of deposit. Here, humic material and organic matter is present, likely incorporated into the deposit after accumulation of shell clasts ceased, perhaps through the growth of vegetation on the surface and the deposition of leaf litter. Vegetation growth can contribute to shell breakage as roots travel along crevices in shell sculpture and fracture valves as their diameters expand (Claassen, 1998, p. 57). Additionally, since the present deposit surface was exposed for the longest period in the history of the deposit, it is subject to the most damage by mechanical processes. These most likely include trampling by humans and animals, no doubt exacerbated by the frequent number of surface fires, which reduces shell integrity (Villagran, 2014). The radiocarbon chronology is of short duration for the entire vertical WP-SM72 deposit, suggesting relatively rapid accumulation and subsequent breakage at each exposed surface where fragmentation processes occurred.

T. granosa is the dominant taxon, comprising 97.13–50.79% of fragmented and complete molluscan clasts (>2 mm) across all spits by weight. Particle sorting terminology is used to describe the variance of particle size within a sedimentological unit, i.e., grain size uniformity. Particle size distribution of *T. granosa* clasts by individual spits (Fig. 12) shows that half of the deposit consists of bimodal, poorly sorted, coarse gravel-sized clasts (e.g., spits 10–20 cm and 30–60 cm). Within the 60–70 cm spit, the particle size distribution is polymodal, poorly sorted, fine gravel-sized clasts, with a mean clast size of 9.62 mm. The lowest three spits are either bi-modal (70–80 cm and 80–90 cm) or trimodal (90–100 cm), with moderately sorted, coarse gravel. The 20–30 cm spit is unimodal, with moderately sorted, gravel-sized clasts. The modality of these samples is considered to reflect *T. granosa* valve fracture in place, as opposed to reflecting the mode and energy of sediment transport as is typically applied in sediment analysis. The *T. granosa* valve fracture pattern is not linear with either depth or time.

The first peak in the particle size distribution of 22.4 mm is explained by the presence of complete (or near complete) valves that failed to pass the 22.4 mm diameter apertures. This peak largely reflects the ability of intact *T. granosa* valves to pass through the screen across its shortest axis, that is, the valve height (Claassen, 1998). Whole *T. granosa* valves within this deposit measured via sieve aperture all have a particle size diameter of <44.55 mm and >11.20 mm. All *T. granosa* complete valves therefore have a height of between 44.55 and 11.20 mm, falling within the known parameters of *T. granosa* valve heights across their modern geographic distribution (Faulkner, 2010). Fragmented valves within these size ranges occasionally exhibit minor chipping or abrasion to the edges of the valve or perforations around the centre of the valve but are otherwise intact. After the 22.4 mm peak, there is a sudden drop in values to 16 mm and values generally stay low until 5.6 mm where they increase again. All samples throughout the column exhibit this pattern, suggesting that when *T. granosa* valves fracture, they do so in a predictable way. It also suggests that the same mechanisms of fracture occurred repeatedly throughout the formation of the deposit, albeit to different degrees, depending on the exposure time of each surface, and the relative repetition or intensity of mechanical stress.

The second most dominant species, *M. hiantina*, exposed to the same site formation and taphonomic processes, records a different history of clast preservation (Fig. 13). *T. granosa* and *M. hiantina* are similar sized bivalves (30–80 mm shell length for *M. hiantina*; Barkati et al., 2006) and are both composed of aragonite. However, *T. granosa* has thick radial ribs and shell walls, and a cross-lamellar microstructure (Faulkner, 2013). *M. hiantina* on the other hand is flatter and composed of both composite prismatic and homogeneous microstructures (Shimamoto, 1986). Overall, *M. hiantina* valves have a lower mean clast size than *T. granosa* (8.71 mm compared to 44.55–11.20 mm), and no intact valves of this species were recovered. It is likely that due to the fragility of *M. hiantina* compared to that of *T. granosa*, valves of this species fragmented more rapidly under the same set of conditions (Zuschin and Stanton, 2001), and fell through the deposit into the voids between the whole *T. granosa* clasts below. Consequently, their presence at a particular depth within the deposit may not reflect the temporal interval of their collection or deposition. This is particularly important for archaeologists, who tend to assume that horizontal proximity is synonymous with contemporaneity.

The WP-SM72 example demonstrates two important points. The first is that the fragmentation and weathering of shells is not time dependent. One might imagine that this would be the case if all shells were deposited as whole valves, and conditions were uniform. However, processes are more likely to occur unevenly through time. Mechanical processes such as trampling or compaction by vehicles, for example, may affect an exposed surface while leaving the internal portions of a deposit relatively unchanged. Under these conditions, pressure is high and localized. While the potential of overburden as a mechanism for shell fragmentation is recognized, and high overburden pressure will compact calcareous sediments (Sterianos, 1988), pressure from people or vehicles is unlikely to create much compaction of layers beneath the surface of a shell deposit, where the weight of the potentially destructive agent is relatively small compared to the weights borne by seafloor deposits in the Sterianos study. The second point is that different shellfish species are likely to break down under the impact of mechanical and chemical processes in different and distinctive ways, depending on morphological and structural characteristics unique to each species.

5.2.2. Case Study Two: JW1705, Janaba West

The Janaba West column JW1705 is half the thickness of WP-SM72 and the distribution of fragments and whole clasts is different (Fig. 14). The molluscan taxonomic composition by weight of the column is dominated by *C. fasciatus* clasts. This species is present at all depths within the column, yet reduces dramatically below 25 cm. The particle size distribution of *C. fasciatus* gravel sized clasts (>2 mm) varies with depth (Fig. 15), with larger sized particles (>11.2 mm) generally representing the whole valve width (the shortest diameter of the intact valve). Whole *C. fasciatus* valves are only found within the 12–18 cm and 18–25 cm spits. For *C. fasciatus* clasts >2 mm, the upper 12 cm of the column features bimodal moderately sorted, fine gravel sized clasts, while the following two spits (12–25 cm) are unimodal, moderately sorted to moderately well sorted, medium gravel-sized clasts. At 33 cm the distribution changes from bimodal, moderately sorted, medium gravel size to unimodal, moderately well sorted, medium gravel size. The basal spits (38–48 cm) are fine gravel-sized clasts with those at 38–43 cm depth being very well sorted, and, at 43–48 cm depth, they are well sorted. Mean *C. fasciatus* clast size is greatest within the 0–12 cm and 18–25 cm spits. The reduced variance in particle size of *C. fasciatus* clasts within the bottom two samples indicates a fragmentation process that is somewhat uniform and has reduced all particles to a similar size.

Also of interest are the thousands of small complete valves (≥1 mm) dominated by Cerithioidea gastropods (N=14,993), notably, *Pirenella conica* (N=2247). The species *Pirenella conica* is a small Potamidid gastropod (common shell length 2.3 mm) with an interesting ecology. It occupies littoral to upper littoral zones within euryhaline marine lagoons and mangrove estuaries (Taraschewski and Paperna, 1981; Zuschin and Ebner, 2015). Modern observations demonstrate this species can occur with high abundance in the low intertidal in modern Red Sea habitats, with their shell valves deposited in the upper tidal zone via low energy wave action (Zushin and Ebner, 2015a, b). Also present within the column are highly fragile thin walled gastropods such as *Cavolinia* sp. (sea butterfly) and parasitic sea snails (Eulimidae). These are located throughout the vertical distribution, with the highest values found in the lower half of the column (25–48 cm). The large increase in “other taxa” (the remaining 46 molluscan taxonomic groups) recovered below 25 cm also suggests that marine processes such as wave action played a role in forming these lower sediments, transporting small exoskeletons of various fauna from the intertidal zone in a beach setting. The foraminifera *Sorites orbiculus*, considered an indicator of past intertidal sediments at Janaba Bay (Abu-Zied et al., 2011), was also recovered as complete tests from the 25–48 cm portion of the column, albeit in small numbers (N≤16 per sample) with one broken test from the 18–25 cm sample. Counts were highest within the two samples 38–43 cm (16 and 15 respectively). The absence of whole foraminifera in the top 25 cm suggests that depositional modes switched from marine to terrestrial, with anthropogenic shell deposition able to commence subsequent to the coastline moving southward and remaining undisturbed by marine incursion. This probably occurred prior to 4500 cal BP (25 cm depth), also indicated in Fig. 6.

Interpreting the Janaba West example is somewhat complicated by the marine influence involved in the deposition of shells at this location. If the presence of *C. fasciatus* with a C14 date of 7205±115 cal BP can be considered evidence of anthropogenic discard, as has been observed in other shell deposits in the area, the particles at these depths were likely fragmented in place upon the surface of the cemented coral prior to burial by later marine sediments. In any case, the amount of *C. fasciatus* present in these basal two samples is very small (<2 g per sample). Considering the nature of the exposed coral platform on which they rested, it is likely that most anthropogenic material deposited here was scoured and mixed by wave action as sea level encroached until a sufficient accumulation of sediment built up and sea level receded. Considering the mean particle size of the two dominant gastropods (by weight) over time, JW1705 shows some linearity between shell clast size and age, generating similar mean particle size values for *C. fasciatus* and *Chicoreus* sp. clasts prior to around 5000 cal BP (Fig. 16). *C. fasciatus* and *Chicoreus* sp. have different valve size and wall thickness, so for clasts of both species to become nearly the same size at the same time implies that the mechanical processes at work reduced large objects more rapidly than smaller ones (Sterianos, 1988). The top 25 cm of the column, largely unaffected by tidal regimes shows results more similar to the example from Wathayn, where structurally reinforced thick valves are more resistant to fracture than those that are small and thin walled when the main mechanism of breakage is likely to occur via surficial mechanical processes such as trampling.

In the Wathayn example, situated out of the range of past sea level incursion during the Holocene, marine influences are not likely to have contributed sediments after shell accumulation commenced. Only small numbers of Eulimidae (N≤16) for the whole deposit were recovered. No larger foraminifera were found (>1 mm). Particle size reduction of shells throughout the column is therefore related to processes occurring in place as opposed to those that may occur via the transport medium such as wave transport. Linearity in mean particle size between species through time as observed for JW1705 is, however, less apparent for the Wathayn example (Fig. 12). This may indicate insufficient exposure time for fragmentation to occur, and high and localized accumulation in comparison to other processes. When comparing the fragmentation of *T. granosa* with the bivalve *Marcia hiantina* within the same deposit, it is apparent that bivalve species do not fragment in the same way even under the same set of conditions. In both case studies, where whole shells valves are deposited by human agents on an exposed landform (especially regarding bivalves where meat extraction occurs without significant damage to the valves), it is likely that the variations in thickness, shape, sculpture, and microstructure of a shell valve determine the likelihood of mechanical fracture via mechanisms such as trampling, with thicker more structurally robust valves resisting breakage (Farinati and Zavala, 1995).

6 Discussion

These results lead to a consideration of three themes of wider significance: the methodologies used in the sampling and quantification of shells and other material from shell deposits; the archaeological implications of formation and deformation processes, in particular their impact on assessments of rates of accumulation; and the interpretation of the size and shape of deposits, especially those that form prominent, mound-like structures.

6.1 Methodologies of sampling and quantification

In a recent review, Parkington and Brand (2020) contrast shellfish remains with those from larger bodied animals suggesting that shellfish are easy to sample, count, measure, weigh, and turn into dietary contributions, and are less susceptible to post-depositional changes than other midden components. The results from this study suggest the need to assess such conclusions carefully.

Firstly, deposits that are formed in coastal environments must be carefully investigated to determine the mode of deposition. It cannot be taken at face value that a given deposit is either geogenic or anthropogenic, and it is likely that different processes interact throughout deposit formation and after deposition once anthropogenic discard has ceased.

Secondly, the volume of material in shell deposits poses a challenge. As illustrated here, comparison of shell deposits requires a detailed sampling design when assessing all components of the deposit. While changes in sampling strategies during excavation (e.g., reducing sample volume), and changes to the level of analysis applied to different samples (e.g., inconsistent subsampling methods or changing of screen sizes used as a cut off point for sorting procedures e.g., Faulkner, 2013; Morrison, 2013a, b; Thomas and Mannino, 2017) may seem appropriate given deposit sizes, these introduce biases, the results of which are difficult to control for. Although standardised methods of sample collection, sieving, weighing, and splitting shell deposit sediments (e.g., using a mechanical splitter as opposed to quartering or scoop methods) to gain an appropriate proportion of sediment for analysis were advocated many years ago (Bowdler, 1983; Butler and Campbell, 2004), consistent application of any given methodology within a single deposit (e.g., Jerardino, 1997; Jerardino and Yates 1997; Klokler, 2008) or between deposits (e.g., Jerardino 2010, 2012; Faulkner, 2013; Morrison, 2013a, b) remains uncommon. The approach applied here shows how screening all sediment through many nested sieves combined with a standardised subsampling strategy can reveal information about the differential breakage of different molluscan species.

Shell deposits, regardless of their regional setting, are not *only* composed of macroscopic shell. The shell that remains is often highly fragmented, the amount of fragmentation varies throughout the vertical extent of a single deposit, and the mechanisms of fragmentation can vary. Breakage is in turn significant because of the impact on quantification. For example, MNI (Minimum Number of Individuals) calculations provide a proxy to estimate the meat yield within a given sedimentary body, from which estimates such as population size and occupational intensity follow (Thomas and Mannino, 2017, p. 57). MNI calculations rely on identifying specific parts of an organism within a sample, typically subject to sieving or screening. If a shell deposit is fragmented, as is the case for the shell deposits examined here, an estimation of MNI is likely to represent the robusticity of a particular shell (or portion of shell) and its resistance to breakage, rather than an independent assessment of the number of individuals consumed. Additionally, if size categories are omitted, as a consequence of in-field screening, small broken objects will be unrecoverable, and MNI values potentially distorted. Indeed, it is for these reasons that other metrics such as NISP (Number of Individual Specimens) are advocated. However, NISP counts are complicated by similar issues including sampling techniques (particularly screening methods), the identifiability of specimens, the equal weighting of objects of different size, and the assumption that all specimens are equally affected by breakage (Grayson, 1984).

An example from this study that makes the point is the analysis of taxonomic frequencies at the Janaba West site of JW1705. Visual inspection and initial analysis of the deposit surface suggested that the large taxon *Chicoreus sp* as dominant. However, careful analysis of rates of fragmentation and size of fragments using the methods described in this study shows that *C. fasciatus* is the dominant taxon in all layers of the deposit except at the base, reaching maximum figures of 90%, and that *Chicoreus* is largely absent except near the top of the deposit where its representation does not exceed 20% in the sampled column (Fig. 10).

Therefore, sampling and quantification are not straightforward, and comparisons between the results of different studies may be compromised both by the intrinsic sedimentological properties of the deposits being compared, by differences in the structural properties of the shells of different species under analysis (and different classes of faunal remains such as vertebrate bone) and their differential resistance to degradation, and by the different methods used in their sampling and analysis.

The approach advocated here provides a relatively simple method of analysis that can be widely and consistently applied to any deposit, subject only to the limitation of the bulk samples available from excavation and the time available for their analysis. The method is relatively labour-intensive but that is true for very nearly all techniques that involve the analysis of the shell material itself from deposits that may contain hundreds to thousands of cubic metres of material and the remains of millions of mollusc shells. As such, the method provides the data needed to assess post-depositional effects at an appropriate scale.

Analyses such as the use of petrographic thin sections and X-ray diffraction can provide important additional evidence about fragmentation and other diagenetic effects such as dissolution and bleaching (e.g., Villarreal et al., 2015), but for reasons explained earlier, these methods were not applicable to the deposits in our case studies.

6.2 Interpreting shell deposits: rates of accumulation

Recognizing shell deposits as dynamic, fluid sediment bodies where morphology and composition change through time by a variety of processes—only some of which are human—alters the way we interpret deposits as they appear today. The conception that a sedimentary deposit contains objects of interest from which "natural" processes can be subtracted to ascertain "cultural" processes (*sensu* Schiffer, 1988) is not applicable to shell deposits, where much of the sedimentary matrix is "natural", comprising the shells of animals, yet can also be "artefactual" in the sense that it is the result of human action (Stein, 1992).

Assessing all the components that make up the deposit and understanding their shape and structure allows an understanding of how each component differentially contributed to the growth and reduction of the original deposit. Sterianos (1988, p. 72), for example, describes the relationship between the nature of calcareous soil particles and their ability to resist fracture under load. Potential breakage increases with soil particle size, amount of thin-walled shell fragments, angularity of grains, presence of hollow particles (such as gastropods), and uniformity of soil gradation (i.e., smaller particle sizes act to distribute load on the coarse-size fraction).

> "As particle crushing increases, the particle size distribution of the material changes, the total contact area increases, the contact stresses between particles decreases and crushing slows down and eventually reaches a limit for a given level of effective stress." (Sterianos, 1988, p. 72)

In addition to the ability of shell taxa to resist fracture, the magnitude of deposition and deposit location are likely to determine shell deposit persistence (Behrensmeyer et al., 2005). Although fragmented valves are present in all samples in this study, their presence may not always equate to the past location and therefore timing of mechanical stress. Intact large valves are comparatively more stationary within the deposit, but small valves and fragments are likely to be more mobile (Koppel et al., 2017). Voids between large clasts permit the downward movement of particles by vibration, and/or water percolation (Williams et al., 2020). For example, the proportion of fine sediment is highest near the exposed surface of the deposit, where fragmentation occurs and windblown sands, silts, and organic matter form part of the deposit. Downward force, vibration, and percolation can all move matter downwards where it travels through voids between whole clasts and begins accumulating towards the base of the deposit. Therefore, what may appear to be stratigraphically intact deposits are shown on further investigation to be the outcome of continuous post-depositional processes of alteration.

These considerations are especially relevant to the calculation of accumulation rates, which reflect not only shell deposition, which can occur via different agencies and processes in different environments but also shell decomposition. How shells decompose in turn reflects both the microenvironments in which they were deposited and their degree of exposure to physical and chemical degradation, and also the robustness of the shell itself. The rate of deposit formation is therefore not a simple function of age and depth. Shell deposits also act as sediment attractors, such that their composition today reflects not only shell deposition but also the accumulation of other materials reflecting growth of vegetation and sediment movement by people and other agents such as wind or water. Results reported here suggest that measurements of the vertical thickness of the shell deposit, and a linear interpolation of time assumed when applying the rate calculations (e.g., Stein et al., 2003; Letham et al., 2017) relate not to one process but several. Vertical accumulation measurements of shell deposit thickness reflect accumulation, breakage, attrition, dissolution, and diagenesis of shell clasts, as well as the introduction of sediment from other sources, and are not a simple function of the quantities of shells originally discarded in one place by human activity. When calculating accumulation rates for individual shell deposits therefore, 'rates' may reflect different depositional modes, the ability of specific taxa to resist physical and chemical weathering in a particular depositional setting, microenvironment, and time frame, rather than the rate at which the shells were originally accumulated by human agents alone (Villareal, 2015).

In both our case study regions, multiple radiocarbon dates have demonstrated highly variable rates of shell accumulation between different deposits, and in the Wathayn case variable rates of accumulation both vertically and laterally within individual deposits. At Wathayn, rates appear to vary across an order of magnitude from <10 cm per hundred years to >100 cm per hundred years (Holdaway et al., 2017). In this group WP-SM72 is one of the fastest with the whole deposit apparently accumulated within less than 100 years while the lowest rate elsewhere is 0.75 cm per 100 years based on simple age depth calculations. In Farasan, JW1705 is one of the slowest (considering the entire column) with a rate of 1.14 cm per 100 years (Hausmann et al., 2019). Considering the upper 25 cm alone, the rate would be around 1.25 cm per 100 years while the nearby mound of JW1727, with a thickness of 2 m, accumulated within a period of 16 to 88 years if models assuming linear rates of accumulation are used (Bailey et al., 2019, p. 599).

A first question is how far these very different rates of accumulation are reflected in the results of the sedimentological analysis. We would expect slowly accumulating deposits to be exposed to higher rates of attrition and degradation than rapidly accumulated deposits. Our results provide some support for this hypothesis, showing both a higher overall degree of fragmentation and progressively increased fragmentation with increased age and depth at JW1705 as compared with WP-SM72, where episodes of increased fragmentation alternate with layers of reduced fragmentation. However, the comparison is complicated by the different shell taxa present in the two regions and the different structure of their shells. A more complete test of the relationship between fragmentation and rates of accumulation would be to compare deposits of different accumulation rates in the same region, where the potentially confounding variable of differential shell structure could be better controlled for. Shell deposits and samples for such a test are present in both regions and are one way in which the sedimentological approach could be further developed.

A second question is how far rates of accumulation need to be modified to take into account alternative depositional agents and post-depositional and diagenetic loss of material. Shell deposits not only increase in size and thickness with progressive addition of new layers of shell material and other sediments, they also tend to decrease over time because of degradation, compaction, and other post-depositional processes. Both formation and deformation processes are time dependent. As a consequence, rates based on the dates and thickness of a deposit incorporate both a growth factor and a “shrinkage” factor. We might expect that the older the deposit or the slower the rate of accumulation, the larger the shrinkage factor, and the greater the tendency for measurement based on the present-day thickness of the deposit to underestimate the original rate of accumulation. In the Farasan group, for example, Hausmann et al. (2019) propose a distinction between sites located on the immediate shoreline with generally large and rapidly accumulating deposits, and sites situated tens to hundreds of metres inland, ‘post-shore sites’, with smaller deposits and slower rates of accumulation. In some cases, this group also includes some of the oldest shell deposits on the island, JW1705 being an example of this type. The shoreline sites are interpreted as primary processing sites located closest to the source of shell food; the post-shore sites are interpreted as habitation sites located for reasons other than convenience of shell food processing (e.g., for shelter or better access to water or supplies of other food resources). The slower rate of shell accumulation in this case is attributed to greater distance from the shoreline and the reduced incentive to carry unprocessed shell food in quantity over greater distances than are necessary. Despite the difference in rates of accumulation in the two types of location being nearly an order of magnitude it remains an open question as to whether the contrast in rates of accumulation has been exaggerated because of systematic differences in rates of deformation. This is another case where comparative analysis of deposits using the sedimentological approach would provide relevant new information.

6.3 Interpreting mound shape and size

As with accumulation rates, so with the ultimate size and shape of a deposit, it is likely that the mounded shell deposits that exist are the product of a variety of processes that have led to progressive modification and alteration. We therefore need to use caution when making inferences based on what is visible today.

From the presence and composition of shell deposits, we can infer that people collected whole shellfish and discarded their empty valves in concentrations of material on exposed landforms. In both our case studies, people processed large numbers of shellfish rapidly and efficiently and discarded the shells in particular places. The accumulated mounds of shell indicate landforms where it was convenient to leave the shell behind after processing. However, the reasons why shells were repeatedly discarded in particular places to form discrete mounds needs careful consideration.

The simplest hypothesis is that the shell mounds accumulate where they do because they are the closest and most convenient place near the shoreline to set up camp, light a fire, and prepare a meal of molluscs after they have been brought ashore from the collecting ground. The labour costs of transporting molluscs in the shell are notoriously high because of the high shell to meat ratio, and processing the shells on the nearest convenient spot is an obvious response, even if the meat is removed and transported elsewhere for later consumption (Hardy et al., 2016). The shells accumulate where they are because of the unnecessary cost of carrying the discarded shells further away to dispose of them. Shell deposits also provide a dry, well-drained, and relatively comfortable surface to camp on, especially if the shell surface is compacted. In the Farasan Islands, extensive scatters of shells are sometimes associated with the remains of stone-built structures located a short distance inland from the shoreline, suggesting the use of the shells as interior flooring material. Shell deposits can also easily be moved aside or excavated to create, pits, wind breaks, or shallow graves for human burials (two of which are reported from one of the Farasan shell mounds (Bailey et al., 2013c)). More substantial accumulations of shell in other parts of the world were modified to create structures such as causeways, canals, plazas, and mounds (Thompson and Andrus, 2011; Schwadron, 2013).

The shell accumulation may have other intrinsic attractions, including partially buried artefacts and other materials discarded by previous occupants that can be re-used and growth of economically useful shrubs in the calcareous soil (Cribb, 1996). In the Weipa environment, shell mounds may have been attractive to repeated occupation because they represent the only dry surfaces in an otherwise flooded coastal wetland during the wet season and the early part of the dry season (Bailey, 1994, 1999).

An alternative hypothesis is that shells were deliberately placed in discrete places on the shoreline in response to more subtle motivations. For example, Oxenford et al. (2007) report that Caribbean fishermen who collect the giant conch (*Strombus gigas*, a larger version of the *C. fasciatus* common in the Farasan deposits and similar in size and form to the other quite common Farasan species *Chicoreus ramosus*), refrain from dumping the processed shells on the seabed because they believe this would cause the live molluscs to avoid the areas used for dumping. Robins et al. (in Bailey, 1999, p. 107) suggested that shell deposits on the Queensland coast of the Gulf of Carpentaria to the west of Cape York were not lived on as camp sites but were deliberately created according to ritual beliefs about waste disposal. Extrapolating from these examples, we might surmise that the shell collectors of Farasan and Wathayn refrained from throwing discarded shells back into the water from processing sites on the shoreline to avoid polluting the live shell beds. The dominant species in both regions prefer specific environments and substrates. *C. fasciatus* is a grazer that prefers sandy shallow bays and seagrass beds around reefs with low tidal energy (Poutiers, 1998; Alsharekh et al., 2014), while *T. granosa* prefers sandy mud substrates in mouths of rivers with a shallow tidal gradient bordered landward by mangroves (Pathansali and Soong, 1958; Broom, 1985). Depositing large quantities of shell into the sea could potentially alter the substrate to the detriment of the living shell beds. Coastal hunter-gatherer communities in other parts of the world are known to have a keen practical awareness of the conditions that favour shell growth and may even take steps to promote improved growth conditions (Moss, 2013). What is at issue here is as much about beliefs in the relationship between the dead and the living as about practical knowledge and understanding. Both of course might be implicated in the gathering and discard of shells. Cultural beliefs that seem odd to us should not be ruled out because of their seeming implausibility.

These examples illustrate how difficult it is to disentangle the impacts of different processes responsible for the formation and deformation of shell deposits whether they be environmental, ecological, behavioural, or cultural in origin. Testing between hypotheses of mound formation resulting from ritual as opposed to practical motivations might seem especially challenging, but a sedimentological approach designed to identify the various processes and rates of formation and deformation that gave rise to a given shell deposit might be expected to provide relevant data to discriminate between some alternative hypotheses. The key point is that the form and shape of a deposit as it appears today is just the current state of an ongoing series of processes involving many different variables.

Nothing can reliably be inferred from its current form without investigating these underlying processes and developing suitably sensitive methods to unravel their varying contribution.

7 Conclusion

The presentation of shell deposits as permanent, large, mounded, forms encourages a conception of an intentional structure, fixed through time. The analyses described here use a different conceptual framework. Instead of analysing the overall structure as a single entity, each clast is treated as an individual object whose source, transport, persistence, and modification is dependent on one or more agencies operating within a landscape, only some of which are initiated by human action. Several complementary analytical techniques are required to understand how these processes work together. Muckle (1985) discussed the difficulty in attributing fragmentation patterns directly to specific processes. A sedimentological approach within a comparative framework can assist in teasing out these problems. Where similar patterns occur across varying geographic conditions with different cultural histories, these may reflect the physical and chemical composition of the clasts themselves and contribute to the interpretation of individual deposits and their relationship to the wider landscape setting within which they occur, reflecting specific agencies operating at various spatial and temporal scales.

In this study we have focused on processes leading to changes in the composition of shell deposits, their rate of deposition, and their final shape. The shell deposits as they appear today are the result of a combination of geomorphic and anthropogenic processes that are closely inter-connected and have contributed to the formation and modification of the sedimentary body throughout its existence. While it is always tempting to seek behavioural inferences directly from archaeological materials, the history of shell mound studies shows that the match between what is found archaeologically and what people did in the past is rarely simple. The results of this study underline the need to pay detailed attention to the different processes that contribute to the formation and post-depositional deformation of shells and shell deposits, if flawed interpretations of their cultural, economic and behavioural significance are to be avoided.

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Figure captions

Fig. 1. Shell deposits around Albatross Bay, Cape York Peninsula, Australia.

Fig. 2. Shell deposits on the Farasan Islands, southern Red Sea, Saudi Arabia

Fig. 3. The shell deposit WP-SM72, Wathayn, post excavation, looking south towards the mangroves. The large shell deposit visible in the background beyond the tents is WP-SM77

Fig. 4. Stratigraphic profile of trench end wall, WP-SM72, Wathayn

Fig. 5. The shell deposit JW1705, Janaba West, during the course of excavation, looking west-south-west. To the left beyond the two standing figures is the original inlet, now a dry, flat sandy surface. To the right, two large shell mounds are visible in the distance, located on the palaeoshoreline on the western side of this former inlet

Fig. 6. Stratigraphic profile of trench end wall, JW1705 Janaba West. NB: Layer 2 is not visible in the end wall profile of the section. The radiocarbon determination OXA-31168 on marine shell was sampled from Layer 1 in the trench side wall at 5 cm depth and is not displayed here

Fig. 7. Sedimentary components per spit, WP-SM72, Wathayn

Fig. 8. Molluscan clasts per spit (>1 mm), WP-SM72, Wathayn

Fig. 9. Sedimentary components per spit, JW1705, Janaba West

Fig. 10. Molluscan clasts per spit (>1 mm), JW1705, Janaba West

Fig. 11. Whole and fragmented molluscan valves per spit (>1mm), WP-SM72, Wathayn

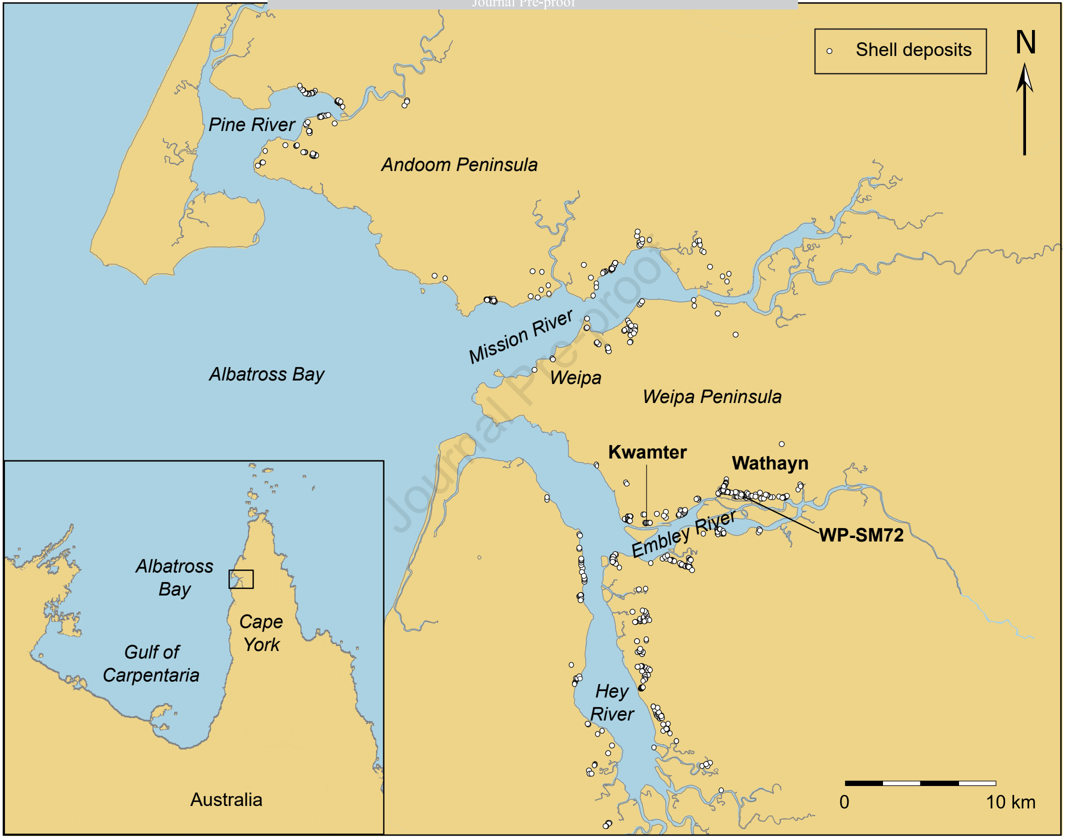
Fig. 12. *T. granosa* particle size distribution (>2 mm) per spit, WPSM72, Wathayn

Fig. 13. Mean particle size of *T. granosa* and *M. hiantina* clasts per spit, WPSM72, Wathayn

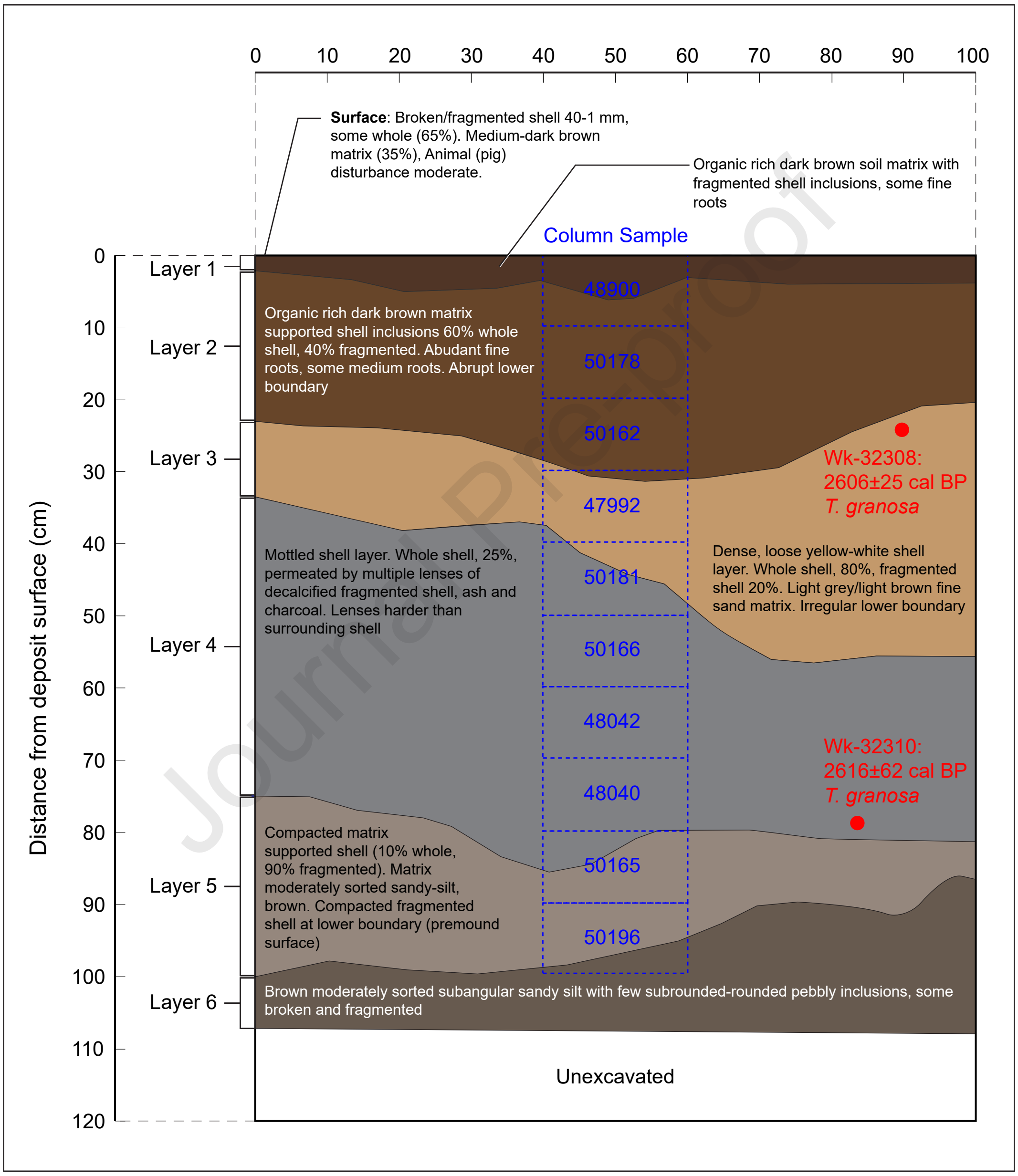
Fig. 14. Whole and fragmented molluscan valves per spit (>1mm), JW1705, Janaba West

Fig. 15. *C. fasciatus* particle size distribution (>2 mm) per spit, JW1705, Janaba West

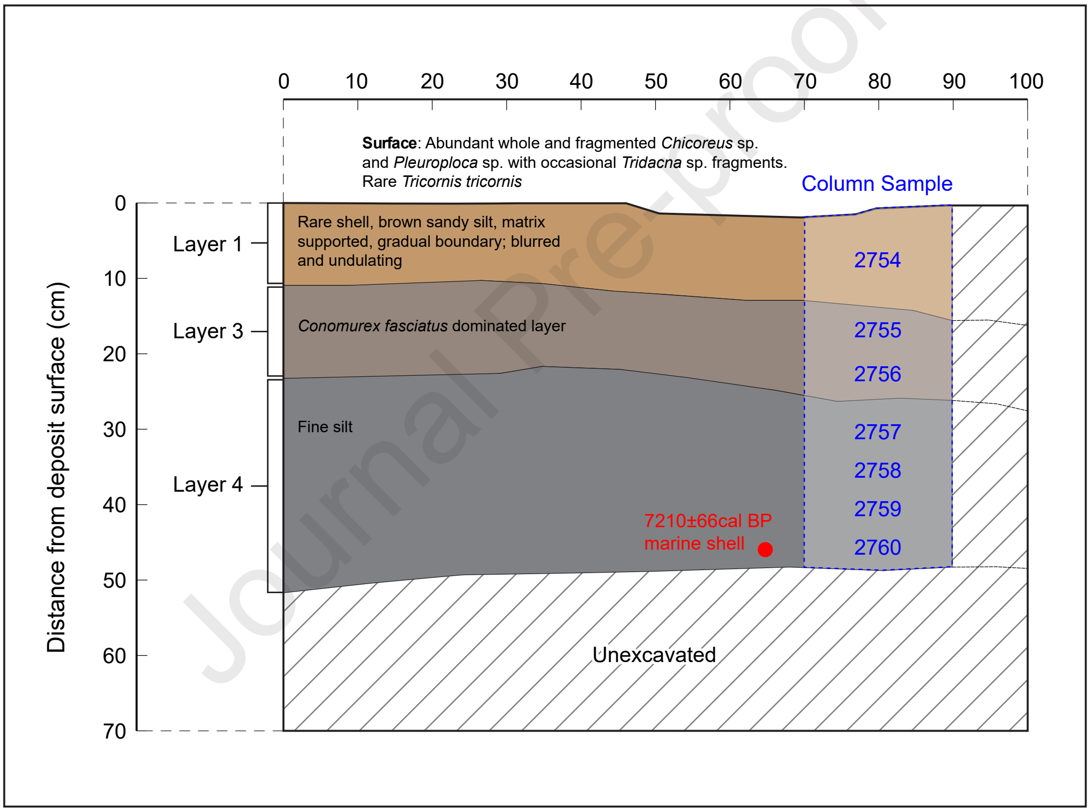
Fig. 16. Mean particle size of *C. fasciatus* and *Chicoreus* sp. clasts per spit, JW1705, Janaba Bay

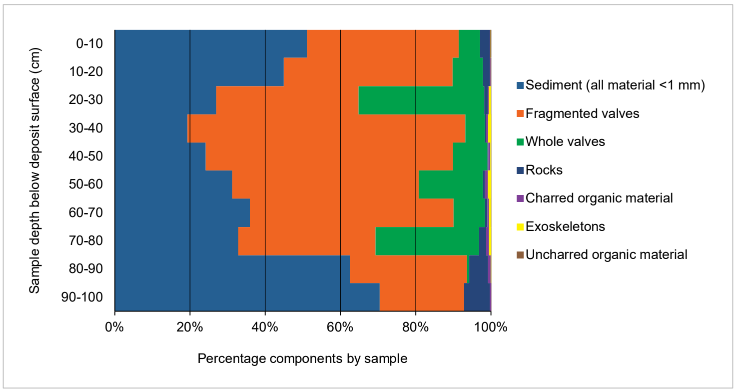

Shell deposits
N
Pine River
Andoom Peninsula
Mission River
Albatross Bay
Weipa
Weipa Peninsula
Kwamter
Wathayn
Embley River
WP-SM72
Hey River
0
10 km
Albatross Bay
Cape York
Gulf of Carpentaria
Australia


Shell deposits
N
West Mandhar
Ad Dissan
Sajid
Sindi Sarso
Mandhar
Sarad Sarso
Kaira
Humr
Khur Maadi Bay
Zufaf
JW1705
Farasan Al-Kabir
Janaba Bay
Dushuk
Abkar 'Uqayli
Qummah
Salubah
Jazirat Dumsuq
0
10 km
Egypt
Saudi Arabia
Red Sea
Sudan
Farasan Islands
Yemen
Ethiopia

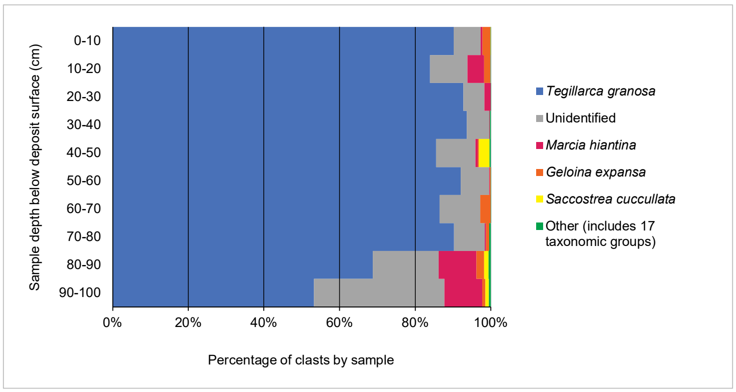


0 10 20 30 40 50 60 70 80 90 100
Surface: Broken/fragmented shell 40-1 mm, some whole (65%). Medium-dark brown matrix (35%), Animal (pig) disturbance moderate.
Organic rich dark brown soil matrix with fragmented shell inclusions, some fine roots
Column Sample
48900
50178
50162
47992
50181
50166
48042
48040
50165
50196
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Distance from deposit surface (cm)
0 10 20 30 40 50 60 70 80 90 100 110 120
Organic rich dark brown matrix supported shell inclusions 60% whole shell, 40% fragmented. Abudant fine roots, some medium roots. Abrupt lower boundary
Wk-32308: 2606±25 cal BP *T. granosa*
Mottled shell layer. Whole shell, 25%, permeated by multiple lenses of decalcified fragmented shell, ash and charcoal. Lenses harder than surrounding shell
Dense, loose yellow-white shell layer. Whole shell, 80%, fragmented shell 20%. Light grey/light brown fine sand matrix. Irregular lower boundary
Wk-32310: 2616±62 cal BP *T. granosa*
Compacted matrix supported shell (10% whole, 90% fragmented). Matrix moderately sorted sandy-silt, brown. Compacted fragmented shell at lower boundary (premound surface)
Brown moderately sorted subangular sandy silt with few subrounded-rounded pebbly inclusions, some broken and fragmented
Unexcavated

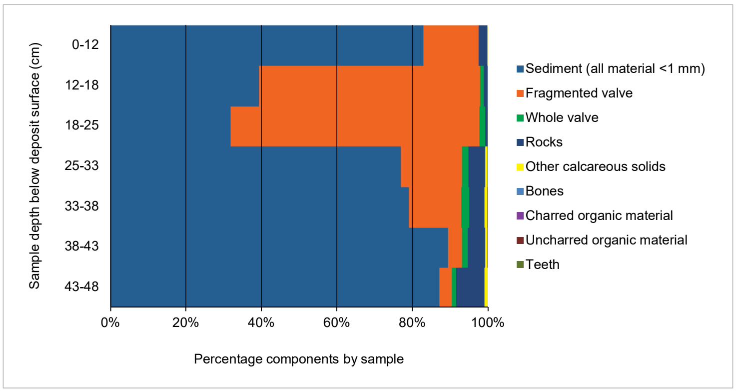

0
10
20
30
40
50
60
70
80
90
100
Surface: Abundant whole and fragmented *Chicoreus* sp. and *Pleuroploca* sp. with occasional *Tridacna* sp. fragments. Rare *Tricornis tricornis*
Column Sample
Layer 1
Rare shell, brown sandy silt, matrix supported, gradual boundary; blurred and undulating
2754
Layer 3
Conomurex fasciatus dominated layer
2755
2756
Layer 4
Fine silt
2757
2758
2759
2760
7210±66cal BP
marine shell
Unexcavated
Distance from deposit surface (cm)
0
10
20
30
40
50
60
70



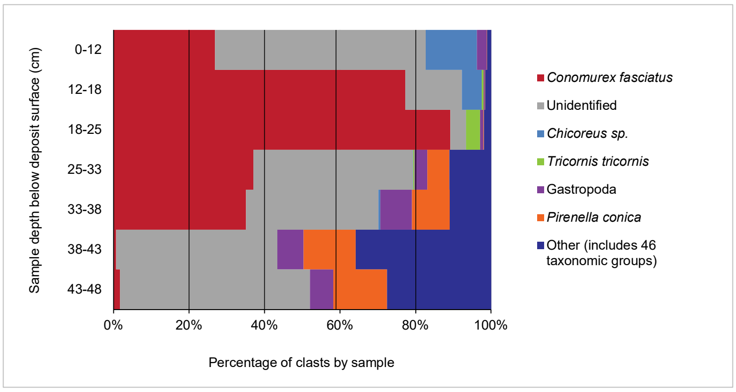
Sample depth below deposit surface (cm)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
0%
20%
40%
60%
80%
100%
Percentage components by sample
Sediment (all material <1 mm)
Fragmented valves
Whole valves
Rocks
Charred organic material
Exoskeletons
Uncharred organic material



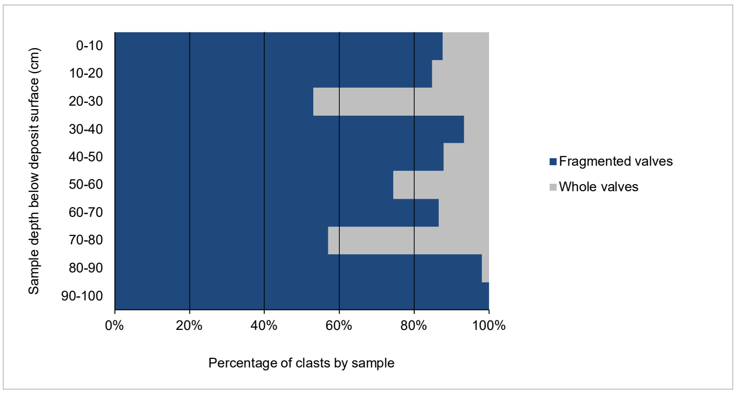
Sample depth below deposit surface (cm)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
0%
20%
40%
60%
80%
100%
Percentage of clasts by sample
Tegillarca granosa
Unidentified
Marcia hiantina
Geloina expansa
Saccostrea cucullata
Other (includes 17 taxonomic groups)

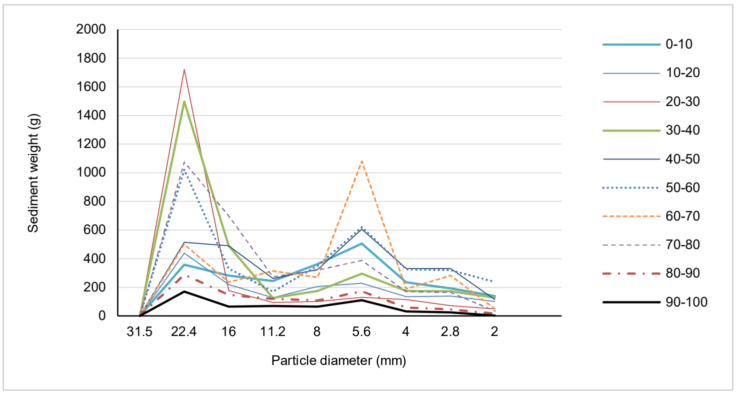


Sample depth below deposit surface (cm)
0-12
12-18
18-25
25-33
33-38
38-43
43-48
0%
20%
40%
60%
80%
100%
Percentage components by sample
Sediment (all material <1 mm)
Fragmented valve
Whole valve
Rocks
Other calcareous solids
Bones
Charred organic material
Uncharred organic material
Teeth

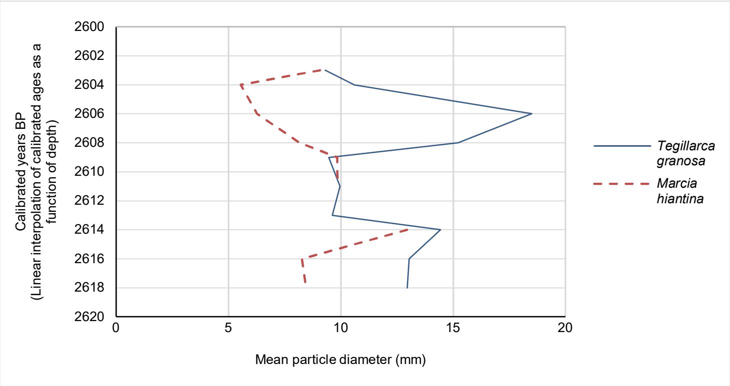


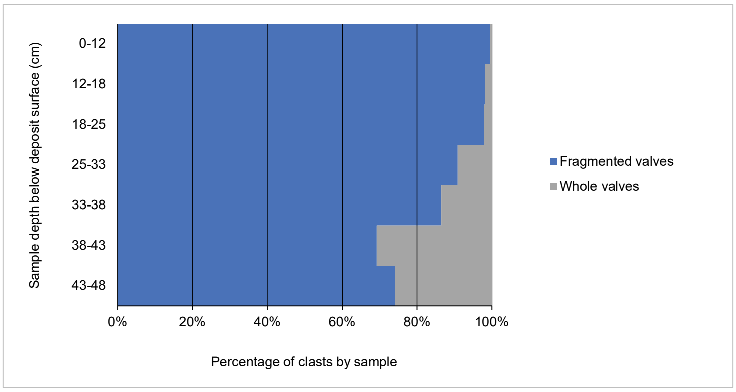
Sample depth below deposit surface (cm)
0-12
12-18
18-25
25-33
33-38
38-43
43-48
0%
20%
40%
60%
80%
100%
Percentage of clasts by sample
Conomurex fasciatus
Unidentified
Chicoreus sp.
Tricornis tricornis
Gastropoda
Pirenella conica
Other (includes 46 taxonomic groups)

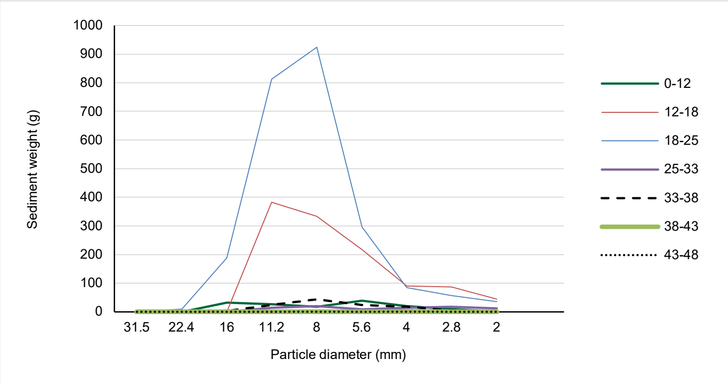

Sample depth below deposit surface (cm)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
0%
20%
40%
60%
80%
100%
Percentage of clasts by sample
Fragmented valves
Whole valves



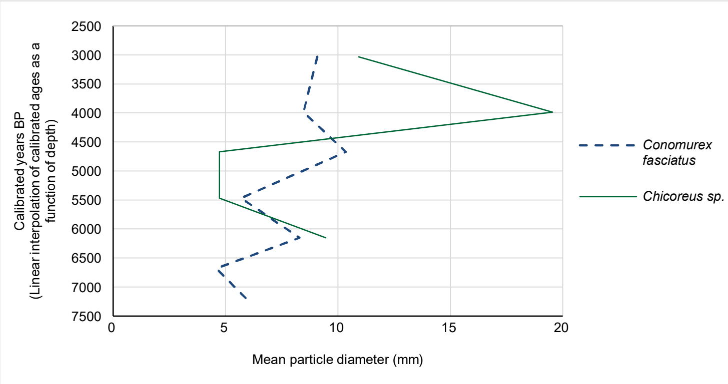
Sediment weight (g)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
31.5
22.4
16
11.2
8
5.6
4
2.8
2
Particle diameter (mm)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100


Calibrated years BP
(Linear interpolation of calibrated ages as a function of depth)
2600
2602
2604
2606
2608
2610
2612
2614
2616
2618
2620
0
5
10
15
20
Mean particle diameter (mm)
Tegillarca granosa
Marcia hiantina


Sample depth below deposit surface (cm)
0-12
12-18
18-25
25-33
33-38
38-43
43-48
0%
20%
40%
60%
80%
100%
Percentage of clasts by sample
Fragmented valves
Whole valves



1000
900
800
700
600
500
400
300
200
100
0
Sediment weight (g)
31.5
22.4
16
11.2
8
5.6
4
2.8
2
Particle diameter (mm)
0-12
12-18
18-25
25-33
33-38
38-43
43-48


Calibrated years BP
(Linear interpolation of calibrated ages as a function of depth)
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
0
5
10
15
20
Mean particle diameter (mm)
Conomurex fasciatus
Chicoreus sp.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: