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From shells to cuscus: Reevaluating *Turbo argyrostoma* exploitation at Matenkupkum during the late pleistocene

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ABSTRACT

This paper re-examines the exploitation of *Turbo argyrostoma* at Matenkupkum, a key coastal site in New Ireland, Papua New Guinea, through the analysis of new data on shell size variation and subsistence shifts. While previous interpretations attributed decreases in *Turbo* size to overexploitation, statistical analyses and environmental considerations suggest a more complex interplay of ecological and environmental factors. The introduction of exotic terrestrial mammals around 20,000 years ago marks a critical turning point in subsistence strategies, highlighting the adaptive flexibility of human populations in response to both environmental changes and resource availability. The results add to global debates on shell midden formation and shellfish exploitation as the study contributes to broader understandings of human–marine resource interactions documented in Pleistocene and early Holocene coastal adaptations worldwide.

1. Introduction

The initial migration of people into New Ireland is the earliest evidence of human occupation in Near Oceania (Roberts et al., 2023). This results in a rare opportunity to examine how early populations adapted to novel island environments. This process highlights the strategies that people employed to transform unfamiliar and resource depauperate landscapes into stable and sustainable living environments. In the Bismarck Archipelago, the exploitation of both coastal and forest habitats reflects not only the adaptability and innovation of early communities but also their responses to environmental fluctuations, cultural transformations, and the emergence of trade and exchange networks. Insights gained from this analysis may extend beyond Island Southeast Asia and the Pacific, contributing to broader understandings of global models of human colonisation by addressing core questions on change in subsistence patterns over time and the how this reflects adaptation to or modification of specific environments and landscapes.

Pleistocene occupation of New Ireland in the Bismarck Archipelago provides the earliest archaeological evidence for human movements off the coast of the continent of Sahul (Gaffney, 2021). The majority of currently excavated sites are caves or shelters that are situated in uplifted coral limestone formations in the northern and central areas of the island (Fig. 1).

The majority of the excavated archaeological assemblages from these sites have not been analysed in detail. To date, faunal analyses of midden assemblages have focused on one Pleistocene site (Buang Merabak) and two sites that were occupied during the Holocene period: Panakiwuk and Balof (Allen and White, 1991; White et al., 1991; Marshall and Allen, 1991).

Buang Merabak is the oldest occupied site on New Ireland, with first occupation at 44,000 years ago (Leavesley, 2006). The faunal collection from Buang Merabak showed that small inland mammals such as bats (particularly *Dobsonia anderseni*) supplemented a marine based diet (largely shellfish) during the Pleistocene period. However, subsistence strategies shifted during the Last Glacial Maximum (LGM) resulting in an increased reliance on inland fauna, particularly of introduced species from mainland Papua New Guinea such as *Phalanger orientalis* (cuscus). At the sites of Panakiwuk and Balof, the number of exotic mainland species increase exponentially between 13,000–9000 years ago as cuscus and (*Thylogale brunii*) pademelon likely become a stable food resource (Marshall and Allen, 1991). The earlier introductions were followed by further exotic species associated with the Lapita arrivals in the late Holocene, including pigs, dog, chicken and *Rattus exulans* (Allen et al., 1989). The last of these, *R. exulans,* may have arrived earlier, with

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bones found in layers at Panakiwuk dating to 8000–13,000 B.P, however this has been attributed to site disturbance (Marshall and Allen, 1991).

Currently, all New Ireland subsistence models rely on these limited analyses which are extrapolated across the Bismarck Archipelago. To gain a more holistic and thorough view of subsistence change over time, the analysis of another Pleistocene site which spans the boundary of the LGM is necessary. Matenkupkum, located in the southern part of New Ireland with occupation from the Late Pleistocene, across the LGM and into the early Holocene, therefore has a key role to play in exploring the current subsistence models applied to island occupation in Near Oceania.

In particular, the exploitation of *Turbo argyrostoma*, a key marine resource, provides critical insights into these transitions. Previous research by Gosden and Robertson (1991) attributed decreasing *Turbo* shell size to overexploitation from anthropogenic shellfishing. This hypothesis was based on a limited analysis that did not address other potential factors for variation in *Turbo* shell size over time. The updated faunal analysis presented here includes a wide variety of taxa including shellfish, vertebrates, and crustaceans. This allows for a holistic approach to be taken in the analysis of subsistence change over time and reveals a more nuanced story where climatic factors like those during the LGM and the introduction of exotic fauna such as *P. orientalis* emerge as major influences on subsistence patterns. This paper revisits earlier interpretations, examining the interplay of environmental and cultural factors in shaping dietary strategies at Matenkupkum. The interpretation of faunal remains may have broad implications on the interpretation of other Pleistocene and early Holocene sites. Shell middens have been a critical way to analyse human coastal adaptations, resource intensification, and environmental change in regions such as Europe, Africa, and the Americas (Milano et al., 2022; Fisher et al., 2020; Bicho and Esteves, 2022). By examining long-term patterns of coastal exploitation at Matenkupkum, this study contributes comparative data to global discussions on foraging societies response to shifting marine productivity and resource pressure during the Late Pleistocene and early Holocene.

2. Background

Despite lower sea levels during the LGM, the islands of the Bismarck Archipelago have always been separate from the Papua New Guinea mainland (Summerhayes and Ford, 2014). This means that the first colonizers to New Ireland must have sailed across from mainland areas. Because of the apparent maritime focus of the first colonizers, Gosden and Robertson (1991) drew on Groube's (1971) 'Strandlooper' theory to suggest that the first communities in New Ireland acclimatized to the relatively depauperate island environment by focussing upon coastal environments.

Originally developed by Groube (1971) for the Lapita colonisation of the Pacific, the Strandlooper theory suggests that although the Lapita peoples are renowned for their movement of horticulture and domesticated animals into the Pacific, it would take time for these crops to establish in their new homelands. Therefore, in the initial stages of island colonisation at least, Lapita potters employed a maritime economy, exploiting stable and abundant resources that had not previously been subjected to human impact. Shellfish play an important role here as they have relatively low procurement costs compared to other faunal resources: they are usually relatively easy to obtain, do not require sophisticated technology, have little pursuit costs, and relatively low search costs if the right environments are available. In their application of this model to the Bismarck Archipelago, Gosden and Robertson (1991) noted the presence of early rock shelters such as Matenkupkum and Matenbek within the coastal resource zone with emphasis on the use of shellfish.

Although the Strandlooper model provides a compelling argument for early coastal sites, the existence of more inland sites in the Bismarcks, including Buang Merabak and Yombon (New Britian), both of which predate 40 kya, appears to contradict the coastal hypothesis. For the inland sites occupied later in time, around the terminal Pleistocene, such as Panakiwuk and Balof, Gosden and Robertson (1991) note the importance of new terrestrial mammal species from the mainland of PNG. They argue that this change in resource use is also a change in mobility patterns, with people changing from being highly mobile to access new and unexploited coastal resources, to bringing the resources home to bolster local resources.

The coastal adaptation model at the heart of the Strandlooper theory has a long history in colonisation modelling of the Bismarcks, with wider application to the continent of Sahul itself, and even wider afield to the Southern Dispersal Route Out of Africa (Bowdler, 1977; Mellars, 2006;

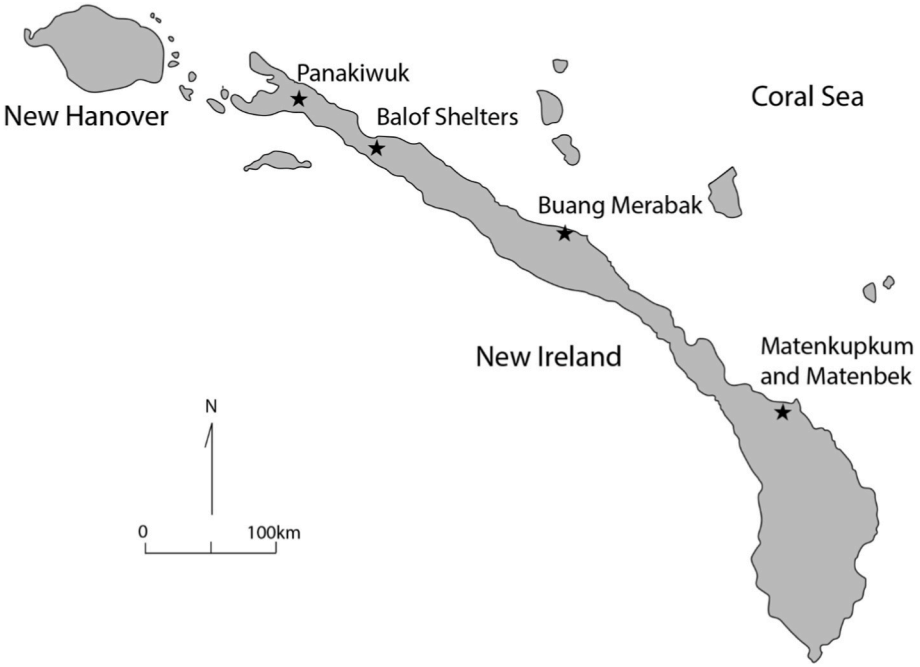

Fig. 1. The Bismarck Archipelago, showing the location of Matenkupkum and other places mentioned in the text.

O'Connell et al., 2010). In more recent years, the coastal model has been retheorised using Human Behavioural Ecological (HBE) models such as patch choice. For example, O'Connell and Allen (2012, 2015) suggest that the first groups of people were coastally adapted and were able to rapidly sail between the coasts of Wallacea in search of new resource catchments or patches. In this case, groups would sail along the coast to exploit subsistence resources at a rapid pace, utilising a given coastal patch, until reaching a point in its productivity (the marginal value), where it was more beneficial to move to a new patch then to change/-adapt strategies within the current one. Coastal patches in particular were seen as efficient for colonising populations as they could be exploited with little change to pre-existing technologies, and as noted earlier, shellfish are considered to be stable and reliable resources in terms of procurement costs.

While Human Behavioural Ecology (HBE) models can be seen to directly influence the focus upon the coast as the most appropriate patch for first colonisers to the Bismarcks, HBE has also influenced models of how the use of the coastal patch is predicted to change over time. As noted above, Gosden and Robertson (1991) mapped changes in both shell size and choice of species at Matenkupkum as a result of human overpredation. This work was influenced by Anderson's (1981) New Zealand shellfish study, one of the earliest ecological models for subsistence which drew upon tenets of optimal foraging theory. For example, Anderson notes that shellfish selection would be governed initially by OFT concepts such as yield (calculated in his study as meat weight), and search time (calculated in his study of shellfish as abundance). He argued that at the first use of a patch, larger individuals would be the focus as they have increased yield. This would result in a selective depletion causing a progressive decrease in shellfish size and force people to collect smaller, less desirable shellfish to compensate. As noted above at Matenkupkum, this could be seen archaeologically by a change in both size of individual shellfish and the range of species utilized over time.

HBE models have therefore been used to explain both the use of the coastal patch at colonisation, and how its use changed over time in the Bismarcks. However, as noted above, this is based on limited detailed data, with focus primarily on shellfish and the introduced marsupial species. More recent analyses of the faunal assemblage from Buang Merabak, for example, have challenged the dominance of the coastal resources and noted the importance of inland rainforest resources such as bats from initial colonisation (Leavesley, 2004). The current research is therefore designed to provide a holistic analysis of a wider range of faunal data sets, while at the same time re-evaluating the basic tenets of the current models of coastal exploitation.

2.1. New Ireland sites

As noted above, there is a lack of analysis of other faunal assemblages in the Bismark Archipelago to compare to Matenkupkum. The faunal assemblage recovered from Buang Merabak constitutes one of the earliest and most continuous archaeological records within the Bismarck Archipelago. Initial human occupation at the site has been dated to approximately 44,000 years ago (Leavesley, 2006), thereby providing a critical framework for understanding adaptive strategies employed by late Pleistocene and early Holocene hunter-gatherer populations in Near Oceania. The faunal data demonstrate a subsistence regime characterized by the exploitation of terrestrial rainforest taxa such as bat and cuscus alongside a consistent use of marine resources.

The earliest cultural deposits are typified by shell middens dominated by large specimens of *Turbo argyrostoma* and *Purpura persica*, indicative of deliberate shellfish collection activities (Leavesley, 2004). These early layers also contain ichthyofaunal remains primarily attributable to reef-associated species and include at least one shark tooth, suggesting nearshore fishing practices (Leavesley et al., 2002). Notably, pelagic taxa are virtually absent, with only a single element identified, providing no substantive evidence for offshore or deep-sea fishing during this period.

Throughout the stratigraphic sequence chiropteran species such as *Dobsonia moluccensis* and *Pteropus* spp. accounted for 40% of vertebrate fauna during the earliest occupation phases at Buang Merabak. This dominance is a sign of specialist bat hunting resulting in bat becoming the primary meat source alongside large rodents including *Melomys rufescens*, *Rattus mordax*, and *Rattus praetor* (Leavesley, 2004). However, there is a clear shift over time with the introduction of cuscus 20,000 years ago. Leavesley argues that there is a distinct shift in foraging and subsistence strategy which can be seen most clearly between 7000 and 3500 years ago as cuscus remains dominate the assemblage (Leavesley et al., 2002).

Analysis of the faunal assemblage reveals minimal change in the relative abundance of marine resources over time. Marine taxa, principally shellfish and inshore reef fish, are consistently present but do not exhibit a clear increase or intensification through the late Pleistocene into the early Holocene (Leavesley et al., 2002, 2004). The stable representation of marine fauna suggests sustained, low-level exploitation rather than a marked shift toward greater marine reliance or specialized fishing strategies. Instead, terrestrial fauna, particularly bats (*Dobsonia* and *Pteropus*) and introduced marsupials like *P. orientalis*, continued to play a dominant role in the subsistence economy (Leavesley, 2004).

The faunal assemblages recovered from Panakiwuk and Balof offer valuable insights into shifting subsistence strategies and site use towards the Holocene. At Panakiwuk, occupation spans between 15,000 and 8000 BP (Marshall and Allen, 1991). Between 15,000 and 13,000 BP the faunal assemblage consists of forest birds, skinks, and large *Rattus* species. A single *Phalanger* bone in the upper layer of this phase marks the earliest appearance of *cuscus* (Marshall and Allen, 1991). However, the most substantial faunal activity occurs between 10,000 and 8000 BP, where the diversity and quantity of remains increase markedly. Species including *P. orientalis*, *Pteropus* spp., snakes, varanids, crocodiles, turtles, and marine fish are represented, indicating a broadening of the subsistence base to encompass both terrestrial and coastal environments. The sporadic presence of marine fauna, including shellfish and fish during all occupation phases reflects intermittent coastal exploitation. Overall, the faunal data at Panakiwuk suggest short-term or seasonal human visitation, with low-intensity use of both forest and marine resources.

In contrast, Balof presents a Holocene sequence from 14,000 to 3000 BP characterized by sustained, anthropogenic accumulation of faunal material across eight stratigraphic horizons (White et al., 1991). Horizon VIII (Pre 14,000 BP) contains a variety of bat, murid, reptile, fish, and shellfish species. *Dobsonia* bat species and *Melomys rufescens* dominate the lower horizons. The upper 70–90 cm of deposit contains a dense array of faunal remains alongside artefacts, pottery, and imported obsidian, indicating intensive and repeated occupation (White et al., 1991). *P. orientalis* was identified abruptly in large quantities from 10, 000 BP onwards alongside *Thylogale brunii*, and *Sus scrofa*. The abrupt nature of these species appearance in the assemblage confirms that they were likely introduced deliberately by humans. A diverse range of marine fish and shellfish are represented in all layers, with the relative abundance of shell increasing in upper layers, particularly Layers I–IV, suggesting a progressive intensification of marine exploitation. Fish bones, while present in early contexts such as Horizon VIII, become more abundant and include greater representation of small-bodied, reef-associated taxa through time, indicative of increasingly specialized fishing strategies (White et al., 1991).

3. Methodology

Matenkupkum is a limestone cave first excavated by Gosden and Robertson in 1985, with a second phase of excavation conducted in 1988 (Gosden and Robertson, 1991). Cultural deposits span from ca. 40,500 to 11,800 cal. BP (Luu, 2021) encompassing key climatic transitions before, during, and after the Last Glacial Maximum. As seen in Fig. 2, a 10 × 1 m trench (Squares D–M) was excavated, with particularly rich

Fig. 2. Plan of Matenkupkum Cave with the excavation trench marked (from Freslov, 1989).

assemblages recovered from Squares G and H (Freslov, 1989). Stratified midden layers contain dense shell deposits (*Turbo argyrostoma*), vertebrate fauna (notably *P. orientalis*), imported obsidian from Talasea and Mopir, and multiple hearths in Squares H–L. Spatial discard patterns suggest regular site maintenance and activity organization linked to natural lighting conditions within the cave.

Matenkupkum provides a rare and complementary view of long-term human occupation and adaptation in the Bismarck Archipelago, capturing shifts in subsistence, exchange, and social complexity from the Late Pleistocene through the Holocene.

3.1. Faunal analysis

All available bone and shell material from squares D-H, G2, and M were analysed. All fauna was washed, bagged, and organised by spit.

Faunal remains were identified using reference collections held at the Otago Archaeological Laboratories. Quantitative analyses employed NISP (Number of Identified Specimens), MNI (Minimum Number of Individuals), and weight metrics to determine the relative importance of different taxa. Results were divided into four chronological phases based on stratigraphic layer (Table 1).

3.2. NISP

The number of identified specimens (NISP) refers to the total count of identified skeletal elements per taxon (Lyman, 2008: 27). NISP values were recorded for all taxa—vertebrate, invertebrate, and shellfish—providing a broad overview of the taxonomic composition across the assemblage. These counts serve as the foundational dataset for further quantification. While NISP provides a general overview of assemblage composition, it does not account for fragmentation or taxonomic importance. Therefore, MNE and MNI were calculated in order to provide a more nuanced interpretation of the assemblage.

Table 1
Summary of phases, layers, and dates of Matenkupkum assemblage (Luu, 2021).

Phase	Layer	Date	Time Period
Four	7	34,011 cal. BP – 40,524 cal. BP	Late Pleistocene
Three	6	23,880 cal. BP – 25,250 cal. BP	Pre LGM/LGM
Two	5,4	17,043 cal. BP- 12,971 cal. BP	Terminal Pleistocene
One	3,2	12,482 cal. BP – 10, 890 cal. BP	Early Holocene

3.3. MNE

The minimum number of elements (MNE) reflects the least number of individual skeletal elements necessary to account for specimens in the assemblage, offering insights into fragmentation patterns and assemblage integrity (Leach, 1997). For fish remains, MNE was determined using the landmark method, wherein specific diagnostic features unique to each skeletal element were used (Leach, 1997: 149–150). For all other taxa, MNE was calculated based on identifiable anatomical portions (e.g., proximal humerus, distal femur). This approach ensured consistency in element identification across all taxa.

3.4. MNI

The minimum number of individuals (MNI) estimates the fewest number of individuals required to account for all identified elements of a given species (Leach, 1997: 330). While typically applied at the species level, MNI was calculated for all classes of fauna to accommodate the limited comparative data available for Pleistocene–Holocene faunal assemblages in New Ireland. MNI was derived by identifying the highest MNE value for a particular element side (e.g., two left mandibles = MNI of 2). For bivalves, MNE values were divided by two to account for paired shells. MNI values were aggregated by spit rather than stratigraphic layer, assuming limited vertical movement of material.

3.5. Meat weight

Meat weight estimates were calculated using established conversion factors, enabling comparisons of dietary contributions from marine and terrestrial resources over time.

MNI values of shellfish, birds, fish, mammals, and reptiles were multiplied by a standardised useable meat weight provided by Smith (2011) and Kirch and Yen (1982: 304-305). Cuscus meat weights were calculated based on the assumption that an adult mammal skeletal weight equals 6.35% of total animal weight (Kirch and Yen, 1982: 304-305).

Meat weight provides a structured way of comparing dietary contributions across vertebrates and invertebrates. However, given that meat weights were calculated using MNI, it is possible that calculations could result in positive MNI bias (Lyman, 2008). This would result in the overcalculation of meat weights for species. The assumption of the average size of individual animals and ambiguity of what is considered ‘edible meat’ may further result in the inaccuracy of meat weight calculations. As such, caution was taken when interpreting meat weight. Furthermore, we suggest that later research combine other methods of quantification with meat weight as we as identify the sex of vertebrates to calculate against MNI and size bias.

3.6. Shell size analysis

Shell size data for *Turbo argyrostoma* focused on shell length as shown in Fig. 3: apex-to-base length (mm) as well as aperture width (mm). A total of 200 shells were measured to the nearest 0.1 mm using standard callipers. This data was subjected to One Way ANOVA tests to evaluate statistically significant changes over time (Table 2). This approach allowed for an investigation of whether size trends reflected environmental stress or human-induced depletion.

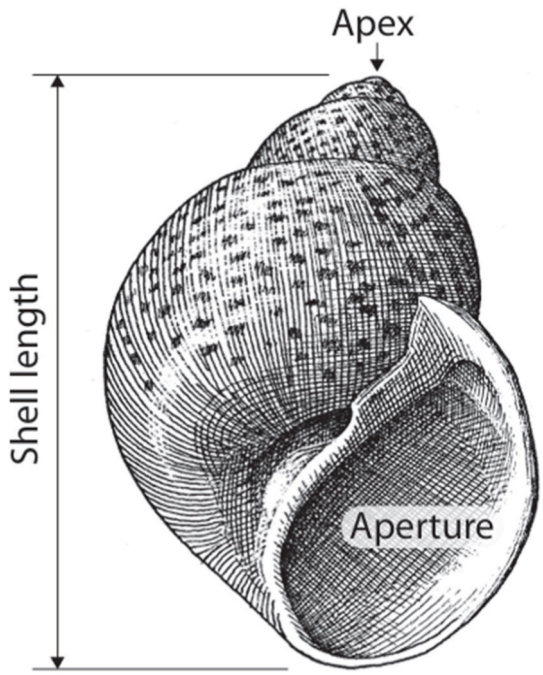

Fig. 3. Diagram of shellfish terminology related to data collection of *Turbo argyrostoma*.

Table 2
Top five Gastropod species across Phases One-Four based on MNI and MNI%.

Phase 1					
Species	*Nerita plicata*	*Patella cinnamomea*	*Patelloida flexuosa*	*Nerita polita*	*Turritellidae*
MNI	3648	1611	1325	1277	986
MNI %	18.75	8.28	6.8	6.56	5.06
Phase 2					
Species	*Nerita plicata*	*Patelloida flexuosa*	*Nerita polita*	*Littorinidae*	*Turritellidae*
MNI	6921	1764	2277	717	569
MNI %	15.04	3.83	4.95	1.56	1.24
Phase 3					
Species	*Nerita plicata*	*Tectarius tectumpersicum*	*Nerita polita*	*Turbo argyrostoma*	*Turritellidae*
MNI	1239	857	777	212	100
MNI %	9.11	6.3	5.71	1.56	<1
Phase 4					
Species	*Turbo argyrostoma*	*Nerita plicata*	*Nertia polita*	*Haliotidae*	*Tectarius tectumpersicum*
MNI	429	262	81	29	25
MNI %	18.89	11.54	3.57	1.28	1.1

3.7. Taphonomy

Taphonomic analysis was undertaken to assess the formation processes affecting the faunal assemblages from Matenkupkum. Weathering stages were recorded for vertebrate remains using a modified version of McGovern-Wilson (1992), with attention paid to cracking and surface erosion. The overall low to moderate weathering observed across all phases was used to infer limited prolonged surface exposure.

Evidence for anthropogenic modification was systematically recorded, including cut marks, chop marks, percussion damage, burning, and shaping. Burning was identified based on colour changes (brown, black, grey, or calcined white) and was recorded separately for bone and shell. Shell artefacts and modified shell fragments were documented based on edge modification, perforation, grinding, and polish, distinguishing cultural modification from natural abrasion. Carnivore and rodent gnawing were recorded where present, although such modifications were rare.

Fragmentation patterns were evaluated through the proportion of complete versus fragmentary elements. Low rates of fragmentation were interpreted as a low rate of trampling and minimal shell processing at the cave site. The level of faunal preservation can influence the interpretation of the analysis as it provides insight into how fauna was treated during the collecting, hunting, and processing phases as well as the general cave environment. However, weathering, anthropogenic modifications, burning, and fragmentation were all identified at low levels throughout all four Phases and will therefore not be discussed in detail further.

4. Results

4.1. Gastropod and bivalve diversity

The composition of gastropod and bivalve assemblages at Matenkupkum reveals significant shifts in dominant species across phases, reflecting changes in foraging strategies and environmental conditions (Tables 2 and 3). For a more comprehensive view of all identified species see supplementary material.

During Phase Four, *Turbo argyrostoma* dominated the gastropod assemblage in terms of MNI and NISP, representing over 60% of the identified gastropod remains. The bivalve assemblage was primarily composed of Mytilidae and *Tridacna crocea*, indicative of a focus on rocky and coral reef environments. The relatively low fragmentation of these shells suggests that they were primarily collected whole and processed minimally.

In Phase Three, *Turbo argyrostoma* remains prevalent but begins to decline slightly in relative abundance, while *Nerita* species and limpets increase in frequency. This shift suggests a broadening of foraging strategies to include more intertidal and rocky shore species. Among bivalves, Mytilidae and *Tridacna crocea* remain dominant, but there is an increase in Veneridae, indicating greater exploitation of sandy shore habitats. Fragmentation rates remain low, suggesting consistent processing techniques.

Phase Two marks a critical transition, with *Turbo argyrostoma* continuing to decline in relative abundance while *Nerita* and limpets become the most frequently identified gastropods based on MNI. The bivalve assemblage shows a marked increase in fragmentation and NISP, with total shell counts rising by approximately 30% compared to Phase Three. The number of fragmented bivalve specimens could be due to taphonomic issures such as increased trampling or shell processing. A more detailed analysis of fragmentation patterns would need to occur in

Table 3
Top three Bivalve species across Phases One-Four based on MNI and MNI%.

Phase One			
Species	*Mytilidae*	*Asaphis volescenis*	*Violencis*
MNI	9	3	2
MNI %	1.14	<1	<1
Phase Two			
Species	*Mytillidae*	*Psammobiidae*	*Mactridae?*
MNI	3	3	1
MNI %	<1	<1	<1
Phase Three			
Species	*Tridacna crocea*	*Veneridae*	*Mytilidae*
MNI	1	1	9
MNI %	50	50	1.14

order to confirm the cause of increased fragmentation. This phase also sees the highest NISP counts for gastropods overall (Table S2.), reinforcing the idea that smaller shell species were being more frequently utilized, possibly due to changing environmental conditions or shifts in dietary preference.

By Phase One, *Nerita* and limpets dominate the gastropod assemblage, while *Turbo argyrostoma* is a minor component. The bivalve assemblage shows a continued emphasis on sandy shore species, and fragmentation rates remain high. The persistence of high fragmentation suggests that these species were being increasingly processed, possibly reflecting adaptations to declining availability of larger shellfish or an increase in tool processing.

These shifts suggest a transition from a reliance on larger, easily collected gastropods like *Turbo argyrostoma* in earlier phases to a more diverse and intensive exploitation of smaller, more resilient species in later phases (See Table S2.). This trend corresponds to Summerhayes' (2007: 15-16) theory of increasing human occupation intensity and environmental pressures 20,000 years ago. The decrease in *Turbo* length therefore aligns with a period of increased gastropod diversity, and the introduction of exotic species, suggesting that dietary reliance on *Turbo* changed due to broader ecological factors. The spike in NISP and fragmentation during this period aligns with broader subsistence adaptations, including the introduction of terrestrial fauna as alternative protein sources.

4.2. Meat weight contributions

Meat weights were calculated to provide conservative estimates of what was likely to have been useable meat in each taxon. Meat weight values are dependent on a variety of factors including environment, animal age, disease, and season of capture (Smith, 2011:114-132; Leavesley, 2004). Despite its variability, Leavesley (2004: 147) argues that "meat weight values are a useful indicator of the dietary contribution of different animals".

Meat weight analysis (Table 4) highlighted a significant shift in dietary composition over time. During Phases Four and Three, shellfish and fish contributed over 60% of total meat weight. However, Fish accounted for 45% and 58% of the total meat weight in Phase Four and Phase Three, respectively. By Phase Two, terrestrial mammals, predominantly *cuscus*, accounted for 65% of meat weight, while shellfish and fish declined to 23% and 6%. While Gastropod and Bivalve meat weight continues to decrease in Phase One Fish meat weight increases to 21%. This dietary shift reflects the increasing importance of introduced terrestrial resources as well as the continued reliance on coastal resources (Fig. 4).

Analysis of MNI and NISP data indicates that *cuscus* remains were absent in Phases Four. A single individual was identified in Phase Three. However, it is not clear whether the presence of *cuscus* in Phase Three was deliberate or a result of site disturbance. The number of *cuscus* increases substantially in Phase Two with a total of 12 identified individuals. This number increases once more in Phase One, where 32 individuals were recorded (Table 5 and Table S1.), representing a substantial shift in dietary preference. These figures suggest a growing reliance on *cuscus* as a staple protein source, likely due to its higher meat and fat yield compared to marine resources.

Table 4
Summary table of meat weights (g) of all major taxa identified at Matenkupkum in squares D-M.

	Bird	Mammal	Crustacean	Chiton	Fish	Gastropod and Bivalve
Phase One	4560	76277.9	81.5	2938	26950	15757
Phase Two	4560	59630.1	27.5	1461	5810	20874
Phase Three	2280	4684	7.5	273	17710	5417.004
Phase Four	4560	3560.1	4	52	10640	4607.004

4.3. Shell size variation over time

Analysis of *Turbo argyrostoma* shells revealed a statistically significant gradual decrease in average size from Phase Four (48.1 mm) to Phase Two (38.67 mm) (Table 2), with a slight recovery to 40.68 mm in Phase One. The One Way ANOVA (Tables 6–8) confirmed statistically significant differences between phases ($p < 0.05$). Notably, the abrupt reduction in size between Phase Three and Four offers some support for the hypothesis that overharvesting may have resulted in deceased shell size over time.

5. Discussion

Previously, migration models to the Bismarck Archipelago have focused on the early exploitation of the coastal zone, followed by movement between coastal areas and inland resources after depleting high-rank shellfish resources (O'Connell et al., 2010; O'Connell and Allen, 2012). The faunal assemblage at Matenkupkum reveals a clear shift in subsistence strategies over time, reflecting a complex interplay between environmental changes, resource availability, and human adaptation that appears to confirm this model. Early reliance on large gastropods such as *Turbo argyrostoma* in Phase Four (over 60% of identified gastropods) suggests an initial focus on high-yield, easily accessible marine resources as suggested by Gosden and Robertson (1991). However, as environmental pressures increased during the LGM, foragers appear to have diversified their resource base, incorporating a wider range of smaller gastropod species such as *Nerita plicata* and limpets.

The parallel increase in bivalve exploitation, particularly of Mytilidae and *Tridacna crocea* could suggest that people were adjusting their foraging practices to maintain protein intake despite changing environmental conditions. Prior to Phase Two, subsistence at the site was predominantly marine based, with fish and shellfish providing the majority of protein. Prior analyses of Matenkupkum have been unable to highlight the importance of fish in early subsistence patterns. However, the current analysis demonstrates a heavy reliance on both reef and deep-water fish species during the early colonisation period (Table S1 and Fig. 4.). However, the arrival of *cuscus* dramatically altered this dynamic. Given that a single *cuscus* provides significantly more protein than an equivalent collection of *Turbo* shells, the shift towards inland hunting represents a strategic adaptation aimed at improving dietary efficiency. Similarly, a substantial increase in fish in Phase One from Phase Two reflects a shift in hunting strategy as people target larger and more efficient food resources (Table 4, Fig. 4, and Table S1.). Despite this, *Turbo argyrostoma* continue to be harvested during the Terminal Pleistocene and Early Holocene. The deliberate introduction of *Phalanger orientalis* and exchange of obsidian into New Ireland from 20,000 BP has been interpreted by Summerhayes (2007) as people intentionally increasing the availability of protein resources in order to support larger populations.

A similar trend has been identified in other New Ireland sites. Although Buang Merabak does not have the same focus on shellfish due to it being located further from the coast, the core idea of communities focussing upon high yield resources with low search costs remains the same. Leavesley (2004, 2005) demonstrates that early subsistence patterns at Buang Merabak consisted mainly of bat hunting as the cave was a natural bat roosting site. In this case, people took advantage of specific patches of local high value resources. However, over time there is a clear shift in resource use, particularly during the Pleistocene/Holocene transition as the introduction of exotic animal species from PNG allowed for a broader range of marsupial fauna to be exploited (Allen et al., 1989; Gosden and Robertson, 1991; Marshall and Allen, 1991; Leavesley &

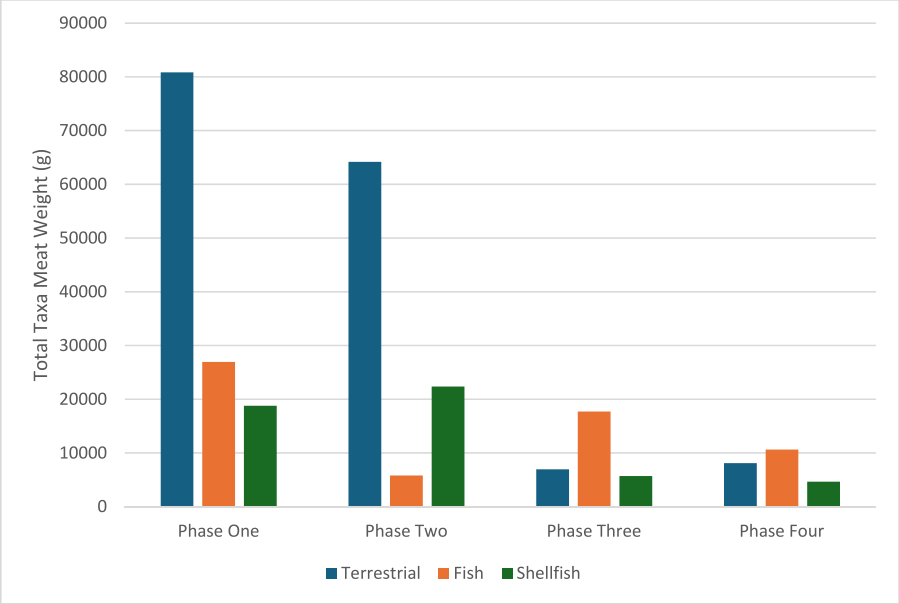

Fig. 4. Meat weight of different fauna types in Phases One-Four.

Table 5
Meat weight of Turbo sp. and *Phalanger orientalis* over time.

	Phase One	Phase Two	Phase Three	Phase Four
Turbo sp.	447	768	636	1287
Phalanger orientalis	74250	58500	4500	0

Table 6
Average length (mm) of Turbo shell from aperture to apex during Phase One to Phase Four.

Phases	Average length (mm)
Phase One	40.68
Phase Two	38.66
Phase Three	44.00
Phase Four	48.10

Table 7
One-Way ANOVA test of *Turbo argyrostoma* shell length between Phase One-Phase Four.

Source of Variation	df	F	P-value
Between Groups	3	9.250961	8.23E-06
Within Groups	238		
Total	241		

Table 8
One-Way ANOVA test of *Turbo argyrostoma* shell length between Phases One-Two, Phases Two-Three, and Phases Three-Four.

Phases	P-Value
Phase One-Two	0.522191
Phase Two-Three	0.034562
Phase Three-Four	0.015035

Allen, 1998). A similar trend has also been identified at later Holocene sites such as Panakiwuk and Balof (Marshall and Allen, 1991; White et al., 1991).

Returning to the original models of colonisation and adaption drawn from HBE, while the Strandlooper model could be considered consistent with the results detailed here from Matenkupkum, it is not entirely sufficient to explain the occupation of Buang Merabak, or the later adaptive changes through the introduction of exotic species. Two changes are proposed: (1) Buang Merabak has demonstrated the need to be more detailed in our understanding of patches, moving beyond the dichotomy of coastal/inland, or coastal/rainforest, and instead focussing upon a more mosaic picture of resource zones (for example the benefits of caves as roosting sites); and (2) to not focus on single data sets to examine adaptive strategies to specific landscapes over time. While the importance of introduced species has been recognised at all of the New Ireland sites, it is only with the holistic type of detailed analysis presented here and by Buang Merabak, that a complete understanding of how changes in one resource are responded to in others. In this case, while the overexploitation of shellfish mirrors that predicted by Anderson (1981), it is also compensated for in other ways through the addition of new resources, changing the meat yield of the local landscape.

5.1. Shift in shellfish size

Gosden and Robertson (1991) previously argued that the decrease in *Turbo argyrostoma* shell size was a direct result of overexploitation. The current study confirms both a decrease in size, as well as reduced use of *Turbo argyrostoma* from Phase Four to Phase Two. As noted by Gosden and Robertson (1991) this could indicate unsustainable harvesting inhibiting the growth of shell species and reducing their overall population. However, consideration must be given to other factors that could influence shell size over time. Environmental factors such as climatic changes associated with the LGM, could also have influenced shell size and availability and need to be considered. For example, decreases in temperatures often slow metabolic rates by limiting oxygen capacity to metabolic functions in shellfish (Rubalcaba, 2024). This results in smaller shell size as less energy is available for growth processes. Such processes may also be impacted for other environmental stressors such as limited food resources, rather than direct anthropogenic depletion.

The LGM (c. 26,500–19,000 years ago) was characterized by lower global temperatures, sea level regression, and increased aridity, which had profound effects on intertidal ecosystems (Roberts et al., 2023). A theory that may explain natural fluctuations in shellfish may be the Temperature–Size Rule (TSR). TSR describes a widespread pattern

among ectothermic organisms, whereby individuals reared in warmer environments tend to grow and mature faster, but at smaller adult body sizes compared to those in cooler environments (Arendt, 2011). This pattern arises from the differing thermal sensitivities of growth and developmental rates: at higher temperatures, development typically outpaces biomass accumulation, resulting in earlier maturation at reduced sizes (Zuo et al., 2012). In marine environments, the TSR provides a useful framework for interpreting organismal size variation in response to past climatic fluctuations. For instance, *T. argyrostoma*, a large marine gastropod commonly found across the Indo-Pacific, may exhibit size plasticity in response to changing sea temperatures. While its precise thermal limits remain understudied, closely related species such as *Turbo chrysostomus* (the gold-mouth turban) exhibit optimal larval development between 26.5 and 27.5 °C and salinity levels of 31.5–35.5 g/L (Sando Hamzah et al., 2021), indicating sensitivity to cooler waters. During the Last Glacial Maximum (LGM), sea surface temperatures in the Bismarck Archipelago were likely 4–6 °C cooler than present, with coastal waters potentially dropping to ~21 °C (Roberts et al., 2023)—well below the developmental optimum observed in *T. chrysostomus*. If *T. argyrostoma* shares similar thermal constraints, such conditions could have driven physiological stress and influenced shell growth, either directly or via TSR-mediated developmental shifts.

The reduction in shell length between relatively colder Phases Four–Three and warmer Phases Two–One supports the TSR, suggesting that warming after the LGM may have contributed to reduced adult sizes. However, temperature fluctuations caused other factors likely intersected with temperature effects. Intertidal productivity may have been reduced during the LGM due to lower algal growth, desiccation stress, or habitat loss from lower sea levels, all of which limit food availability for grazing gastropods (Taoufik and de Vernal, 2008; Mutizabal-Aros et al., 2024; Svane and Ompi, 1993). However, further research is vital to provide more substantive evidence on the effects of ecological stress and climate change on shell size reduction in *T. argyrostoma.* Currently, the abrupt decrease between Phases Four and Three reflects the onset of anthropogenic harvesting pressure while the increase in shell size during Phase One may result from a refocusing on foraging on rocky coast species and terrestrial foraging. This is evidenced by a marked increase in the diversity of gastropod and bivalve species collected during Phase 3 as well as the sudden introduction of exotic fauna (Table S1).

By Phase One, there is a slight recovery in *Turbo* shell size (40.68 mm), likely reflecting the post-LGM stabilization of marine ecosystems. Although further research is required of the faunal assemblages of Panakiwuk, Balof, and Matenbek, it is important to observe fluctuations in shellfish exploitation patterns within the context of long-term environmental variability rather than solely as evidence of human-induced resource depletion.

6. Conclusion

This study demonstrates that the decline in *Turbo argyrostoma* shell size at Matenkupkum may not be attributed solely to overexploitation. Instead, a combination of environmental pressures and cultural shifts may have influenced dietary transitions. The introduction of exotic terrestrial fauna, particularly *cuscus*, provided an alternative protein source, reducing reliance on *Turbo* and contributing to shifts in foraging behaviour.

The findings underscore the resilience and adaptability of human populations at Matenkupkum. The interplay of environmental and cultural factors highlights the complexity of subsistence strategies during the Pleistocene-Holocene transition. These insights contribute to broader discussions of human-environment interactions in the Pacific and beyond.

Author contributions

Joëlle den Toom: Conceptualization, writing- original draft, writing-review and editing, methodology, formal analysis, investigation.
Glenn Summerhayes: Supervision, resources, validation.
Anne Ford: Supervision, Writing-review and editing, validation.
Karen Greig: Supervision, validation.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2026.109903.

Data availability

All data and/or code is contained within the submission.

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