



Reconstructing pre-European marine habitats using archaeological assemblages: A case-study from the Ōtata midden, New Zealand

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ABSTRACT

The Ōtata midden, site R10/139, on Ōtata Island in the Hauraki Gulf, New Zealand, is a stratified site with dates spanning most of the pre-European occupation of New Zealand (cal 1350–1800 CE). This provides a rare opportunity to examine potential anthropogenic changes in the pre-European marine environment. Snapper (*Chrysophrys auratus*) otoliths from three midden layers were analysed for barium (Ba) and strontium (Sr) composition with Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) and the resulting data for the first 1500 μm from the core, roughly equivalent to the first two years of the fish's life, were analysed with Behavioural Change Point Analysis (BCPA). This showed that juvenile snapper behaviours did not change but that Ba concentrations in the second year of life did. This is attributed to anthropogenic landscape changes altering the hydrology of the zone where freshwater mixes into the marine waters of the gulf.

1. Introduction

In this study we examine the evidence for pre-European Māori interactions with the marine environment of the Hauraki Gulf in northern New Zealand, using otolith chemistry profiles of snapper (*Chrysophrys auratus*) from the Ōtata midden as indicators of habitat characteristics. New Zealand was the last major landmass to be settled by humans, with the arrival of East Polynesian voyagers, the ancestors of the Māori, around 1300 CE (Anderson 1991; Walter et al. 2017). In the lower South Island, subsistence activities centred around hunting of the flightless moa (Dinornithiformes), while further north, where moa were less common, the economy was based on cultivation of tropical cultivars, particularly kūmara (sweet potato, *Ipomoea batatas*), supplemented by

fishing and hunting sea mammals. Māori throughout New Zealand maintained social cohesion through continued archipelago-wide voyaging, facilitating movement of high quality lithic and other resources (Walter et al. 2010). By the early to mid-15th century the moa had been hunted to extinction, the South Island became depopulated and widespread voyaging seems to have ceased (Anderson 1989; Anderson and Smith 1996; Holdaway and Jacomb 2000; Worthy and Holdaway 2002). Apart from the moa, at least 30 other marine and terrestrial bird species also became extinct (Duncan and Blackburn 2004; Tennyson and Martinson 2006), seals were extirpated through much of their natural range (Smith 2002; Collins et al. 2014) and forests were extensively cleared for horticulture (McWethy et al. 2014). Resource depression, population growth and increased competition

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appear to characterise this sequence, but the period is also marked by technological and social changes. The development and elaboration of fortified hilltop pā is one example, with agronomic innovations accelerating the settlement of inland areas from the mid-16th century (Gumbley et al. 2003; Gumbley 2021). Captain Cook and the crew of the *Endeavour* described a vibrant Māori society in 1769 (Beaglehole 1955) as did numerous other voyagers, missionaries and traders in the late 18th and early 19th centuries (<https://www.enzb.auckland.ac.nz/>).

In the Hauraki Gulf, north and east of Auckland, early settlements were established at the entrance to the Waitematā Harbour, at Torpedo Bay and the Masonic Tavern site, or on the nearby islands (Fig. 1), such as at Pūharakeke on Motutapu (Nichol 1988), Motunau Bay on Ponui (Nicholls 1964; Sheppard et al. 2011) and Ōtata on Ōtata Island (Furey and Ash 2020, 2021), along with other potentially early sites that have not been investigated (Fig. 1). Settlement began to spread out from these locations in the mid-15th century and Māori began to utilise local rather than traded resources (Cruickshank 2011; Campbell et al. 2019). Occupation of the islands continued, for instance on Ōtata four periods of occupation are evident in the midden up until the 18th century. Numerous pā were built on the islands and around the Hauraki Gulf, particularly on the volcanic cones of the Tāmaki isthmus where the modern city of Auckland is located.

The first settlers in New Zealand brought with them a set of transported landscapes (Kirch 2000) that both included a suite of domestic animals and plants, along with cultural practices that shaped how these domesticates functioned in an ecosystem. These transported landscapes interacted with the found landscapes of the new land. Because settlement is so recent, these interactions are clearly visible in the environmental record (Pawson and Brooking 2013), including the extinction and extirpation of numerous fauna and clearance of large tracts of forest.

Human impacts on terrestrial ecosystems have been a major focus of archaeological research in New Zealand (Anderson 2013) due to the relatively static nature of these ecosystems and the direct interactions

humans have with them. Conversely, marine ecosystems are dynamic and experience more indirect interactions with humans. As a result, unravelling the complexities of human impacts on marine ecosystems is more challenging, leading to them receiving comparatively less attention. Several researchers have concluded that effects, if any, were minor and difficult to disentangle from natural phenomena (e.g., Shawcross 1967; Leach and Davidson 2000, 2001; Leach 2006). Pest eradication on islands leads to increases in seabird biomass and nutrients derived from guano in both land and nearshore environments (Rankin and Jones 2021; Benkwitt et al. 2021), which implies that the arrival of humans, rats and dogs that suppressed seabird populations in New Zealand would have had flow on effects on coastal ecosystems. Māori populations were never large and it is uncertain, for example, whether Māori fishing practices would have had significant effects on fish populations. Leach (2006) and Davidson (2011) suggest that indirect pressures may have been more important. For example, land clearance for gardening may have resulted in increased sediment loads in harbours and estuaries, leading to ecosystem changes in nearshore habitats. Wells et al. (2019) show that growth rates of tuangi (*Austrovenus stutchburyi*), a bivalve, declined by as much as 50 % between 1400 and 1800 CE at several archaeological sites following increased sediment influx into estuaries due to pre-European land clearance. Deforestation alters watersheds and the hydrological regimes of rivers, impacting freshwater sources feeding fluvial sediments into nearshore environments (Cuo 2016; Lyra and Rigo 2019; Restrepo et al. 2015). This potentially affects the quality of estuarine and nearshore habitats, which provide important ecosystem functions for a range of organisms (Litvin et al. 2018).

Recent research has begun to focus more closely on human-environmental interactions in marine ecosystems, benefitting from multi-technical and cross-disciplinary collaborative approaches (Allen and Kahn 2024). Archaeological assemblages offer a unique perspective on former ecosystems and can be used to examine environmental baselines on longer timescales than are otherwise available to the life

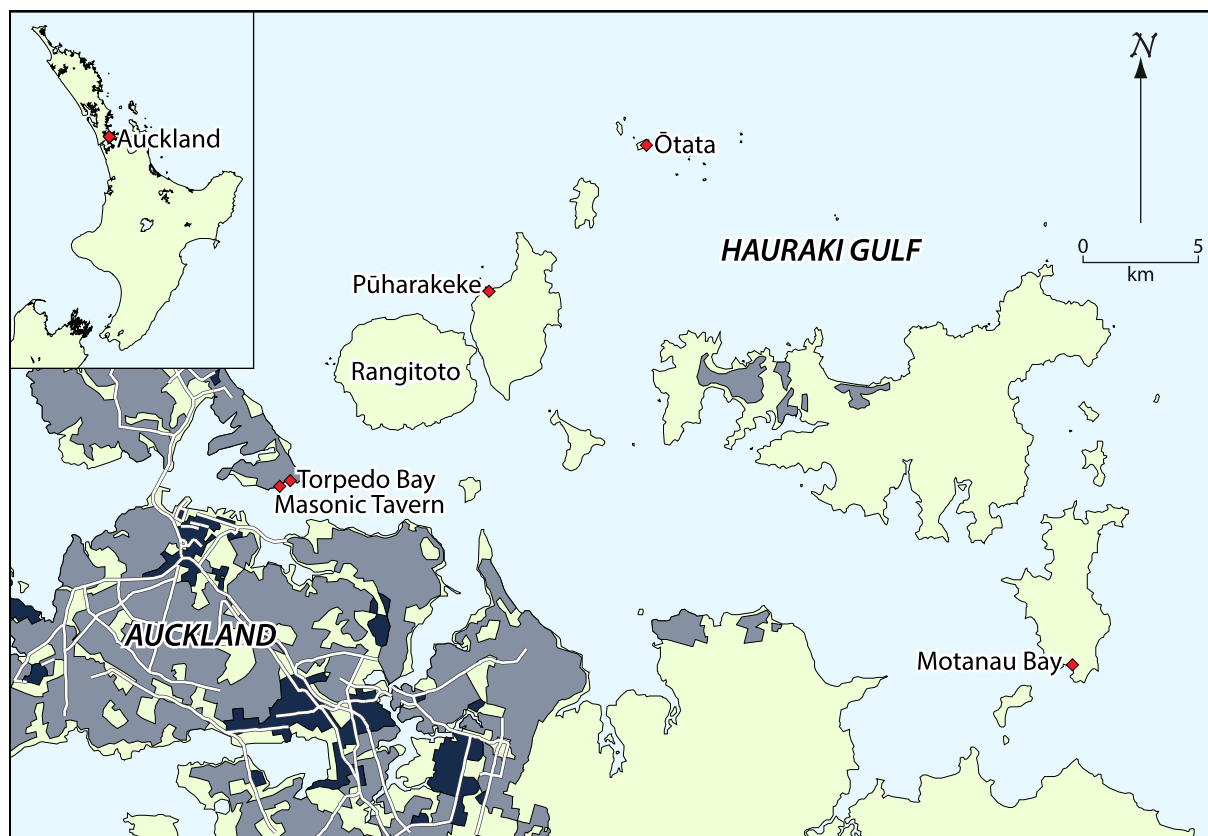


Fig. 1. The Hauraki Gulf, showing archaeological sites mentioned in the text.

sciences. Our research group has previously examined elemental concentrations in snapper otoliths from archaeological and modern samples from the Hauraki Gulf, looking at changes between pre-European and modern environments (Sabetian et al. 2021; Campbell et al. 2021; Lilkendey et al. 2025). In this study we examine a new archaeological dataset from the Ōtata midden, where five occupation layers span the full pre-European sequence.

The Ōtata midden.

Ōtata is a small island (~600 x 500 m with a maximum elevation of

~ 65 m) in the Noises Group at the margin of the inner Hauraki Gulf, where the bathymetry drops away to the cooler waters of the outer gulf (Fig. 1). Archaeological site R10/139 was originally recorded as two layers of midden, but in 2018 a storm and accompanying swells eroded ~ 5 m of the coastal scarp and scoured out the pebble beach, exposing further stratigraphic layers for ~ 50 m along the scarp. Seven excavation squares (Squares A–G) were excavated in the face of the midden and behind it in 2020 and 2021. Five occupation layers and three natural layers were recorded, although not all layers were present in all squares

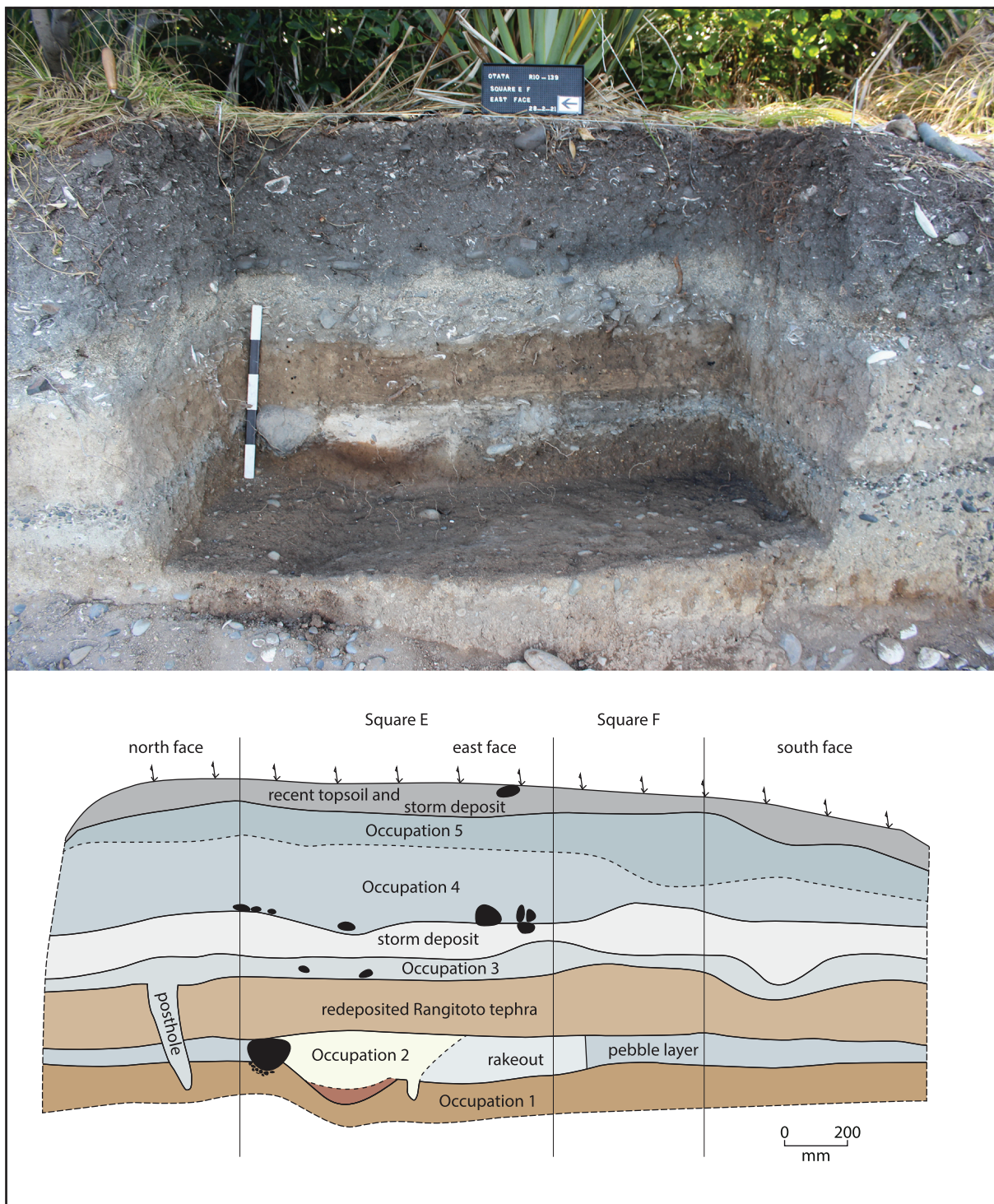


Fig. 2. Square E (1000 mm wide) and Square F (500 mm wide) were excavated 700–800 mm into the face of the exposed midden. They demonstrate the typical stratigraphy for the site. Photo and drawing are not to the same scale.

(Fig. 2). The general stratigraphy is:

A storm deposit from the 2018 storm consisting of water rolled beach cobbles and shell.

Occupation 5, which probably consists of several similar occupations or events superimposed and mixed. The deposit consists of mixed fragmented and burnt shell and fire-cracked rock in a dark charcoal stained matrix. In Square A an intact hāngī (deep earth oven) containing large intact and fragmented beach boulders was dug into and covered by this matrix. The upper 100 mm of the layer was a topsoil containing modern plastic and glass as well as faunal material.

Occupation 4 was present in Squares D, E and F and could be distinguished from Occupation 5 immediately above it. This deposit had more loam, less charcoal, shell and fire-cracked rock but lenses of oyster shell and fish at the base. It seems probable that Occupation 4 is the first of several late events that are distinguished as Occupation 5. The two occupations have indistinguishable dates and for the sake of analysis and discussion Occupations 4 and 5 are treated as one (Occupation 4/5).

Below Occupation 4 was a storm deposit of fine beach gravel and shell fragments 130–200 mm thick, with some cultural material mixed into it.

Occupation 3 was a relatively thin deposit containing shell, fish bone and fire-cracked rock but with notably less charcoal staining than Occupations 4 and 5.

A thick deposit, 200–300 mm deep of redeposited tephra, was present below Occupation 3. This appears to be a slopewash deposit and contains lenses of soil and clay but no cultural material below the upper few mm. This tephra relates to the Rangitoto A and B eruptions dating to 1400–1450 CE (Needham et al. 2011).

Occupation 2 was only present in Square E and consisted of an ash-filled earth oven with rakeout cut into Occupation 1, and occasional cultural material mixed into a surrounding wave deposited pebble layer. This pebble layer was also visible in Squares D, F and G.

Occupation 1 was visible in all squares and was deepest, ~100 mm, in Squares E and F. It contained fish, bird and sea mammal bone, and obsidian and basalt flakes in a fine, clean pebbly beach matrix, but significantly less shell or charcoal. It appears to have been disturbed by waves or storms with small beach pebbles mixed in to the upper parts of the layer by wave action.

Only a preliminary dating programme has been carried out so far. Four terrestrial and three marine samples were submitted to the Radiocarbon Dating Laboratory at the University of Waikato for AMS dating: two each from Occupations 1, 3 and 5, and one from Occupation 4. The results (Table 1) show that Occupation 1 dates to the 14th century CE, not as early as the earliest dates for East Polynesian settlement for New Zealand, but soon after; Occupation 3 dates to the mid-15th to early 17th centuries, after the Rangitoto eruption; and Layers 4 and 5 date to the early 18th century up to modern times, and that these two layers are indistinguishable. A preliminary Bayesian modelling of the dates, using

1400–1450 CE for the Rangitoto tephra (Needham et al. 2011) as an upper boundary for Occupation 1 and lower boundary for Occupation 3, and 1800 CE as a reasonable date for the probable incursion of European material into the site and an upper boundary for Occupations 4 and 5, does not alter the overall periodisation of the occupations, but considerably reduces the uncertainty associated with the marine dates (Fig. 3).

2. Methodology

Snapper (a sparid, or sea bream, not to be confused with tropical snappers, which are lutjanids) is a demersal species inhabiting rocky reefs and sandy bottoms and played a crucial role as a mesopredator in reef ecosystems (Salomon et al. 2008; Parsons et al. 2011, Parsons et al. (2020); Booth 2019). While generally solitary, snapper may form schools during the spawning season (Leach and Boocock 1995; Leach and Davidson 2000; Parsons et al. 2014). As serial spawners, they produce millions of eggs across multiple spawning events, with larvae remaining in open water for approximately 28 days before settling in structured estuarine habitats such as seagrass and mussel beds (Parsons et al. 2014). As they grow, juveniles gradually transition to coastal environments before adopting the broader range of adult fish (Parsons et al. 2013; Francis 1995).

Otoliths are calcified fish ear bones which, as a result of biomineralization, provide a chronology of an individual's habitat history (Disspain et al. 2016). Otoliths exhibit growth bands analogous to tree rings, constantly accreting a calcium carbonate-protein matrix without metabolic alteration, which serves as a natural chronometer for studying temporal fish interactions with their habitats (Campana and Thorrold 2001; Palumbi et al. 2003; Thomas et al. 2017). For example, the chemical profiles of nearshore waters reflect variable anthropogenic and terrestrial input, while oceanic waters tend to be more physiochemically consistent (Izzo et al. 2018). The analysis of otolith elemental profiles provides fine-scale information on the life-history of fish movement patterns and their habitat preferences. Until recently the sclerochronology of otoliths has focused on conventional point analysis multi-tracer methodological approach, which is essentially concerned with using absolute (or averaged) values to establish residency at specific time-points in a fish's life. However, this approach is vulnerable to misinterpretation because various physiological and environmental factors can influence elemental incorporation into the otolith matrix (Hüsey et al. 2021; Sturrock et al. 2015; Campana and Thorrold 2001; Izzo et al. 2018). Additionally, we had to be cognizant of the individual variability in the elemental profiles of archaeological otoliths sampled centuries apart. Sophisticated time-series approaches such as Behavioural Change Point Analysis (BCPA) or Dynamic Time Warping (DTW) can potentially overcome these issues by analysing relative changes among elements rather than absolute values, thus unlocking new insights from the complete otolith elemental profile (Hegg and Kennedy 2021; Sabetian et al. 2021; Arai et al. 2024; Lilkendey et al. 2025). Here, we use BCPA to analyse the chemical signatures of snapper otoliths from

Table 1
Unmodelled radiocarbon results.

Lab no.	Occupation	Material	CRA BP	cal. CE 68 %	cal. CE 95 %
Wk-51779	5	shell	604 ± 28	1650–1825 (68.3 %)	1556–1921 (95.4 %)
Wk-51781	5	charcoal	218 ± 20	1671–1678 (7 %) 1735–1783 (55.5 %) 1796–1801 (5.8 %)	1665–1690 (18.7 %) 1728–1808 (76.8 %)
Wk-53020	4	shell	523 ± 20	1720–1900 (68.3 %)	1680–1960 (95.4 %)
Wk-53017	3	shell	912 ± 20	1380–1520 (68.3 %)	1310–1600 (95.4 %)
Wk-53018	3	charcoal	416 ± 21	1450–1500 (55.9 %) 1600–1620 (12.4 %)	1450–1510 (65 %) 1550–1560 (1.2 %) 1580–1630 (20.3 %)
Wk-53019	1	charcoal	672 ± 19	1300–1330 (27 %) 1340–1370 (25.8 %)	1290–1400 (95.4 %)
Wk-52172	1	bird bone	715 ± 16	1290–1310 (30.6 %) 1360–1390 (37.7 %)	1280–1320 (46.6 %) 1350–1390 (48.9 %)

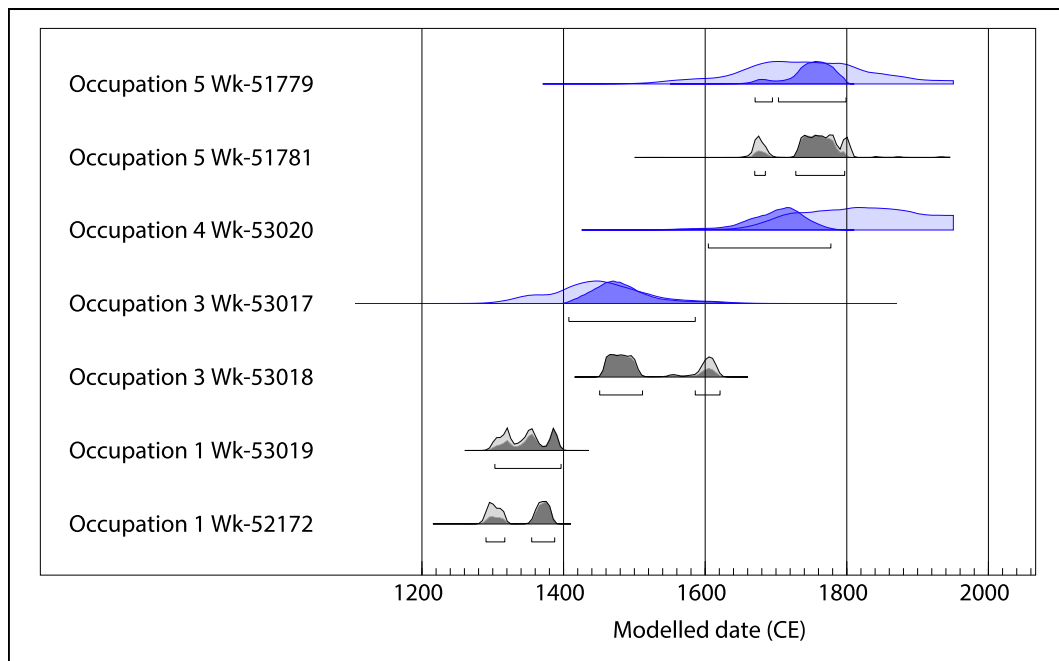


Fig. 3. Bayesian age model for the occupations. The lighter shade distributions are the unmodelled calibrated dates, darker shade distributions represent the results after Bayesian modelling. Terrestrial dates are in grey, marine dates in blue. Distribution bars represent the 95% confidence interval.

the Ōtata midden, which are proxies we use to infer water chemistry and snapper movement patterns.

Five snapper otoliths from each of Occupations 1, 3 and 4/5 were selected for analysis. It must be acknowledged that this is a small sample size, but the analysis is destructive and it was not desirable to destroy all the otoliths from the midden, saving some for future analyses. While 44 otoliths were recovered from Occupation 1, only 8 and 7 were recovered from Occupations 3 and 4/5 respectively.

Otolith assemblage and elemental analysis.

The otoliths were analysed for barium (Ba) and strontium (Sr) composition using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) along a linear path from the core of the otolith to the proximal tip. Sectioned otoliths were fixed to microscope slides and examined using a laser ablation system connected to a quadrupole ICP-MS. An NIST610 glass standard was regularly ablated to calibrate instrument response with NIST612 glass serving as control reference material. Prior to the main ablation, a pre-ablation cleaning pass was executed to eliminate surface contaminants. The core of each otolith was the focal point for analysis, though visually pinpointing its exact location was sometimes challenging. The laser settings for the pre-ablation involved a 75 μm spot size and a speed of 40 $\mu\text{m}/\text{s}$, while the main ablation utilized a 50 μm spot size at 10 $\mu\text{m}/\text{s}$. Both passes were carried out with a laser fluence of 2.5 J/cm^2 and a firing frequency of 10 Hz. A 25 s interval between pre-ablation and main ablation was allowed for background measurements. Data reduction was conducted using Iolite v3.71 software, with calibration based on Ca-normalized NIST610 data following background subtraction. For the controls, the precision for the elements determined was typically less than 2 % RSD for NIST612 and less than 6 % RSD for USGS MACS3. Aberrant isotopic signatures on the edges of otolith transects were cleaned by filtering the ion beam intensity in counts-per-second (cps). All concentration results where Ca was below 15,000 cps were excluded, as this value corresponded to the lower end of the measured values throughout the study (mean cps of Ca was 29,766). This exclusion removed any variations in the element/Ca ratio due to low sample detections at the otolith edges or surface defects (cracks, glues, etc.) that could distort the data. Elemental transects from all otoliths were limited to a maximum length of 3000 μm , covering the juvenile and adult periods for most otoliths (mean

length of all transects was 2935 μm). This was done to prevent bias from transect shapes formed by substantially longer-lived fish. Including their entire life histories could result in clustering due to longer lifespans, obscuring changes in movement or migratory timing between early and modern periods. After trimming, all transects underwent smoothing using three-pass outlier detection with the `tsclean` function in the `forecast` package for R version 4.3.3 (R Development Core Team 2024), followed by a 100-point moving mean. Transects were then re-interpolated to the mean length of all transects (1392 points). Whole transect means of each element/Ca ratio were calculated from this data to perform exploratory clustering.

Behavioural Change Point Analysis.

All otoliths were examined under a compound microscope for periodicity of opaque and translucent zones, reflecting annual growth rings (Francis et al. 1992). To focus on the elemental profile of early life history, it was confirmed that at least two years of growth were represented along a 1500 μm linear path from the core to the distal edge of each otolith. This 1500 μm length was adopted as the standard for analysis, ensuring that the time series from each sample included sufficient representation of the early life stages for all individuals (snapper ages taken from otoliths were generally similar across all Occupations, ranging from 8 to 38+).

The next step involved identifying changes in autocorrelation structures within the standardized concentrations of Ba and Sr within each occupation. Using the `bcpa` R package, we determined the smallest temporal scale that could be analysed, with a window size of 30. Segments between change points detected by BCPA are referred to as bouts.

Prior to clustering, we determined the number of distinct states in the otolith time series using the within-group sums of squares method and serial classification of bouts, following the hierarchical clustering approach outlined by Krzanowski and Lai (1988). The mean Ba and Sr concentrations for each bout were then calculated and used as input for k-means clustering analysis (Hartigan and Wong 1979) in R, utilizing the `cluster` package (Maechler et al. 2019). This clustering analysis was run for each occupation separately, and in each occupation produced three distinct Behavioural States (BS) (Table 2).

We ran the analysis on data collected from each occupation separately. As the snapper might experience different coastal environmental

Table 2
Sr and Ba mean concentrations for each Behavioural State for each Occupation.

	BS	Sr ppm (Mean ± SE)	Ba ppm (Mean ± SE)
Occupation 1	BS 1	1985.98 ± 8.31	25.64 ± 0.43
	BS 2	2969.89 ± 27.51	93.96 ± 0.70
	BS 3	3081.72 ± 12.94	32.97 ± 0.48
Occupation 3	BS 1	1935.67 ± 7.31	16.39 ± 0.17
	BS 2	2916.22 ± 38.93	64.22 ± 1.24
	BS 3	3284.62 ± 14.58	14.09 ± 0.24
Occupation 4/5	BS 1	1802.1 ± 7.84	8.21 ± 0.12
	BS 2	2036.33 ± 26.55	35.04 ± 0.46
	BS 3	3229.66 ± 12.03	16.54 ± 0.15

conditions across time, the grouping of bouts into BS should only happen for otolith data from the same occupation layer. We interpreted the BS based on established understandings of coastal water chemistry. In this context, Sr concentrations can be used as a proxy for relative salinity, with lower Sr concentrations corresponding to less saline, generally estuarine waters, and higher concentrations indicating more oceanic environments (de Vries et al. 2005; Macdonald and Crook 2010; Izzo et al. 2018). Ba is primarily released from clay and transported into the ocean with riverine fluvial deposits (Montaggioni and Braithwaite 2009), thus higher Ba concentrations in fish otoliths are a strong proxy for waters influenced by freshwater discharge (Elsdon and Gillanders 2005).

Once the BS were identified for each occupation, we used the BCPA model to track the movement of individual snapper through these states

during the first two years of their life. The duration of each state, represented by distance along the otolith ablation transect, was calculated, along with the number of state transitions each individual fish underwent. To compare the sequence of states within and between occupations, we calculated the proportion of individuals in each state across all distances measured on the otolith. For each occupation, we created a new time series to visually compare the consistency of behavioural sequences among individuals. The proportion of individuals in each state at different transect distances was used to assess whether the timing of a particular state was consistent across individuals within an occupation. If a state was consistently observed in individuals at a specific transect distance, the proportion of individuals in that state would be high at that distance.

3. Results

In each fish, the first half of the otolith tracks was dominated by the lowest Sr and low Ba concentrations (BS 1, Table 2, Fig. 4). In contrast, the second half of the tracks was characterised by the highest Sr concentrations within each occupation, this time with the second highest Ba concentration (BS 3, Table 2, Fig. 4). Between these two dominant states, we see a short transitional state characterised by mid-level Sr concentrations and highest Ba concentrations (BS 2, Table 2, Fig. 4). This pattern was consistent across all occupations.

The mean proportion of time or residency spent within each BS shows differences among occupations (Fig. 5). Fish in Occupation 1 spent a mean of 42.4 %, 22.4 % and 35.2 % of their time in BS 1, 2, and 3, respectively; in Occupation 3, fish spent 65.2 %, 7.2 % and 27.2 % of their time in BS 1, 2, and 3, respectively; and in Occupation 4/5, fish

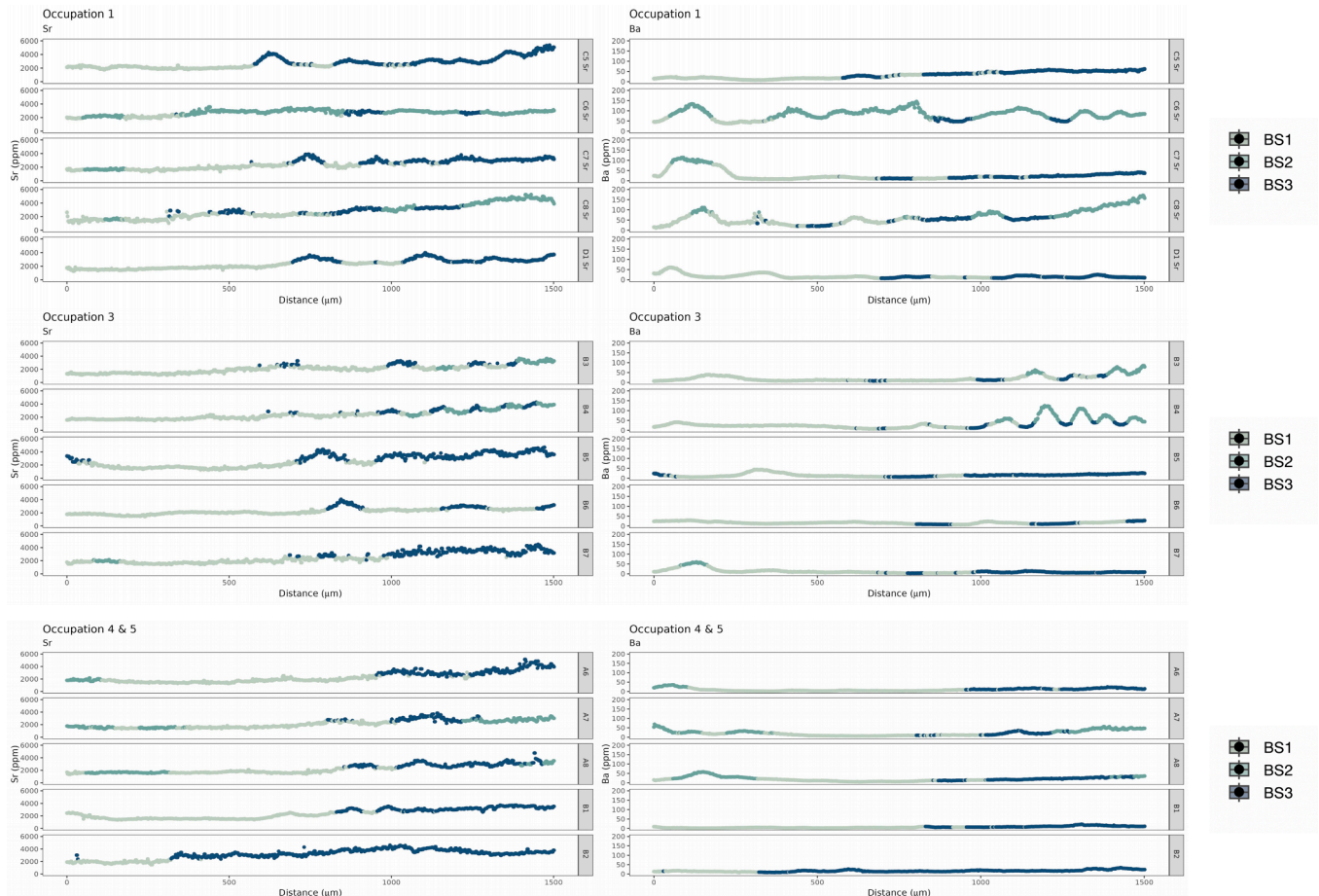


Fig. 4. Strontium (Sr) and barium (Ba) concentrations along laser-ablated transects by Occupation.

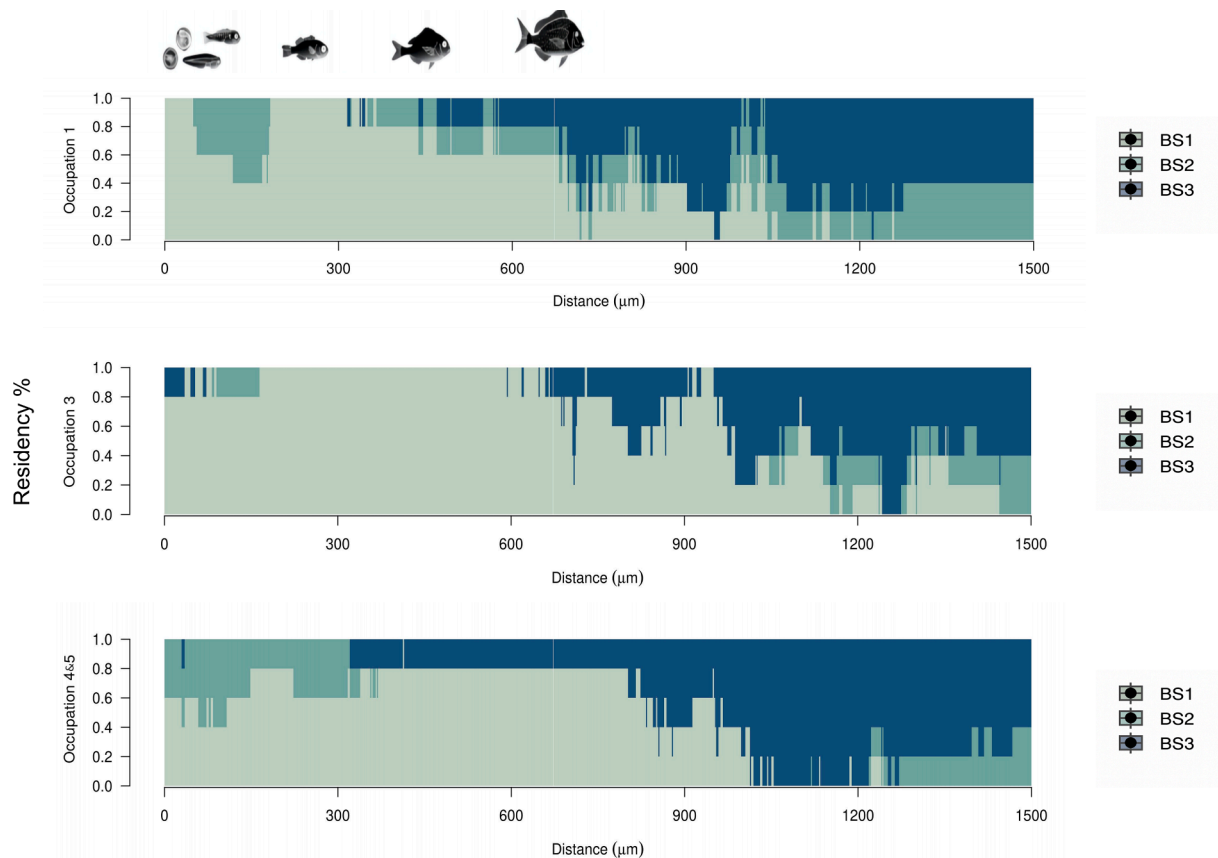


Fig. 5. Mean proportion of residency (%) for each Behavioural State for each Occupation. For reference, we also show drawings of snapper early life ontogeny from larvae to one year of age.

spent 45.8 %, 12.8 %, and 41.2 % of their time in BS 1, 2, and 3, respectively.

The switching behaviour (i.e., the number of times individuals moved between any two BS) during the first two years of life followed a consistent trend across all occupations. The mean number of switches was highest between BS 1 and BS 3, with values of 6.8 ± 1.13 SE for Occupation 1, 8.4 ± 0.78 SE for Occupation 3, and 4.9 ± 0.57 SE for Occupation 4/5. In contrast, transitions between BS 1 and BS 2, and between BS 3 and BS 2, occurred less frequently, with each sample exhibiting only 1 to 2 switches per transect. This pattern likely reflects the lowest time fish spent in BS 2, compared to the other two states.

4. Discussion

Behavioural Change Point Analysis is a statistical method used to resolve fine-scale patterns of animal behaviour and movement. In this analysis we have used BCPA to characterise the environments the fish are resident in rather than their patterns of movement. We assigned three Behavioural States to the results from each location, based on the logic of BCPA, but it might be more accurate to think of them as Residential States. Movement patterns emerge from changing environmental Ba and Sr concentrations revealed in otolith chemistry as juvenile snapper move from one BS to another, with a general movement from BS 1 to BS 3 equivalent to the movement from sheltered, estuarine nursery habitats to increasingly open, oceanic waters.

We have previously used LA-ICP-MS and BCPA to analyse the chemical signatures of pre-European, archaeological (mid-late 15th century) and modern snapper otoliths from the Hauraki Gulf. Using habitats as proxies for behaviour, we showed that pre-European juvenile snapper exhibited synchronized and consistent nearshore movement

patterns during their first two years of life, settling in estuarine nurseries as larvae and progressively moving into more open waters in the first two years of life. In contrast, modern juvenile snapper exhibit chaotic behaviours, moving from estuarine to open waters almost at random. We concluded: firstly, that prior to modern industrial scale impacts on the Hauraki Gulf waters, juvenile snapper were inhabiting structured estuarine nursery environments, while modern juvenile snapper remain further out in the marine gulf waters due to the degradation and destruction of nursery habitat; and, secondly, that our dataset reflected the geographic separation of our sources (outer and inner gulf waters) and did not allow us to consistently examine snapper movement patterns throughout the pre-European period (Sabetian et al. 2021; Campbell et al. 2021; Lilkendey et al. 2025).

The current analysis addresses this latter point and, consistent with our earlier work, has shown that juvenile snapper did not change their behaviours and movement patterns during the pre-European period in the Hauraki Gulf. BCPA has shown that for all occupations, from soon after the East Polynesian settlement of New Zealand (Occupation 1, 14th century CE) to just prior to the arrival of Europeans and their technologies (Occupation 4/5, 18th century), juvenile snapper exhibited the same patterns of early habitat residency and movement, reflecting stable interactions between the fish and their environments. In their first year snapper from all three occupations primarily reside in lower salinity nearshore environments (BS 1). In their second year they increasingly shift to higher salinity habitats (BS 2 and 3). The shelter of abundant sponges and seagrass meadows provides ideal nursery habitats for young snapper, giving protection from predators and allowing them to conserve energy, and as they mature they gradually move out to progressively more offshore environments (Parsons et al. 2014, Parsons et al. (2020)).

While movement patterns did not change over time in the Hauraki Gulf, the BCPA analysis shows that habitat characteristics did, with three similar patterns observed across the occupations. The first was that BS 1 was represented by the lowest Sr and Ba concentrations for all occupations (Table 2), indicating the consistent use of low salinity sheltered nearshore nursery habitats away from any major freshwater influence. The second pattern was that BS 2 was characterised by mid-level Sr and highest Ba concentrations for all occupations. This chemical signature aligns with typical shallow mixing zones in coastal areas where freshwater and seawater converge (Wilson 2005). We suggest that this area also served as a transitional habitat for juvenile snapper. This is supported by the observation that fish in all occupations spent the least amount of time in BS 2. The third and most interesting pattern was in Ba concentrations in BS 2 which were, on average, 1.5 times higher in Occupation 1 than in Occupation 3, and 2.5 times higher than in Occupation 4/5. Despite our small sample size, the trend is clear. Variability of Ba concentrations is typical in tidally influenced coastal systems where freshwater and saltwater frequently mix (Hamer et al. 2003, Hamer et al. (2006); Elsdon and Gillanders 2006; Fowler et al. 2017). Because the Hauraki Gulf is surrounded by many barrier islands, it essentially behaves as a semi-enclosed embayment with restricted mixing with oceanic waters (Boxberg et al. 2020). As a result, ambient Ba levels in such shallow mixing zones are generally expected to be higher than in open ocean waters (Alibert et al. 2003). However, the decline of Ba concentrations between the 14th and 18th centuries warrants closer scrutiny.

Ba and Sr are both alkaline earth metals in group 2 of the periodic table, along with Ca, and their carbonates can be incorporated into otoliths as they substitute for calcium in CaCO_3 (Doubleday et al. 2014; de Vries et al. 2005). However, Ba and Sr behave differently in the marine environment (Izzo et al. 2015). Ba is influenced by a broad range of environmental and biological factors that make its behaviour more complex and variable than Sr. In freshwater, Ba is typically present in a soluble, bioavailable form (Ba^{2+}), which can associate with carbonates as BaCO_3 . However, when this freshwater derived Ba enters the marine environment, both marine bacteria and the relatively high concentrations of sulphate results in barite formation (BaSO_4) (Gonzalez-Muñoz et al. 2012; Martinez-Ruiz et al. 2019), a stable, insoluble, and non-bioavailable mineral.

In the Hauraki Gulf, higher concentrations of Ba in the mixing zones of shallow, coastal waters can be attributed to several key environmental and geological factors. The Gulf's unique hydrodynamics, characterised by the mixing of freshwater inputs from rivers and streams with saline marine waters, create conditions that promote the accumulation of Ba in these regions (Hamer et al. 2003, 2006). Freshwater inputs, such as those from the Waihou River and other smaller streams, often contain elevated levels of Ba derived from natural geological sources (i.e., adsorbed onto clay like minerals) and terrestrial runoff as well as agricultural and industrial activities within the catchment area (McCulloch et al. 2003; Cao et al. 2016). As freshwater meets seawater in the shallower, coastal areas of the Gulf, Ba becomes more concentrated due to the lower water volume and slower flushing times typically associated with these inshore zones.

In the case of the Hauraki Gulf, the Rangitoto volcano was active for at least 150 years, and probably longer, before it ceased erupting around 1450 CE (Shane et al. 2013; Linnell et al. 2016; Allington et al. 2023), which is marked at Ōtata by the tephra layer between Occupations 1 and 3. It was, therefore active during Occupation 1 and the weathering and erosion of newly formed volcanic detritus potentially contributed to further enrichment of Ba in gulf waters at that time (Lein and Kravchishina 2021). The highest concentration of Ba was from Occupation 1 in the 14th century, which falls within the period of active volcanism associated with the formation of Rangitoto. The subsequent declines in mean Ba values in Occupations 3 and 4/5 could, then, be due to the cessation of deposition of volcanic material into the gulf waters. Tephra records show that by cal 1496 ± 6 CE volcanic activity around Rangitoto

had ceased, represented by the tephra layer between Occupation 1 and 3 (Needham et al. 2011; Shane et al. 2013). However, this Ba would seem not to have been in a bioavailable form as the elevated Ba signature does not show up in BS 3 for Occupation 1 when the fish were moving into more open waters closer to the ostensible source of volcanic Ba. This would require it to convert from a stable mineral form to bioavailable BaCO_3 as it reached the transitional mixing zone where the Ba signature is elevated, but this seems unlikely and, while we cannot entirely rule it out as an explanation, there is no clear mechanism by which this could happen.

Another possible explanation lies in altered hydrodynamics of the Hauraki Gulf's mixing zones (BS 2), which are also transitional zones for juvenile snapper, leading to shifts in water chemistry reflected in changing Sr and Ba signatures. High Ba levels show that Ba remains enriched in these mixing zones throughout the pre-European sequence, but this enrichment diminished over time, providing a strong signal of the environmental stressors impacting the gulf's ecosystems. This shift in chemical signatures appears not to be a product of physical processes such as volcanism, rather it seems to be driven by other factors altering the gulf's hydrodynamics and the distribution of its marine resources.

Decreasing Ba levels may be linked to a transition in the Gulf's freshwater inputs or shifting fluvial sediment dynamics, with lower concentrations of Ba in the later occupations suggesting altered freshwater input into the coastal ecosystem (Sinclair and McCulloch 2014). One plausible scenario is deforestation initiated by Māori for activities such as garden clearance (McWethy et al. 2010, 2014), leading to increased sedimentation and changing fluvial inputs, such as amount, frequency and variability of water flows. Deforestation has also been linked to altered rainfall patterns from change in forest structure and increased levels of evapotranspiration (Vertessy et al. 2001; Taylor et al. 2019; de Lima and Tonello 2023). We suggest several possible ways, neither mutually exclusive nor exhaustive, in which this could be reflected in changing Ba levels. The fluvial mixing zone may move further offshore so that it no longer coincides so neatly with the juvenile snapper transitional zone; or sedimentation may directly impact the transitional zone, shrinking the extent of nursery habitats so that their margin moves inshore, away from the Ba rich mixing zone; or the amount and distribution of Ba in marine waters may change; or the mechanics of the mixing zones may be altered. We can't provide a definitive answer, but juvenile snapper in transitional zones are no longer swimming in the same Ba rich waters in later occupations as they were in Occupation 1.

5. Conclusion

We began this paper with an outline of well understood anthropogenic impacts on terrestrial ecosystems in pre-European New Zealand – extinctions, extirpations and deforestation. We then asked, are there parallel processes taking place in marine ecosystems? Terrestrial environments are less dynamic and humans interact with them directly, while marine environments are fluid and human interaction is much less direct, and anthropogenic changes to marine environments are likely to be less obvious. Fish otolith chemistry directly reflects the chemistry of the water and the environments the fish are swimming in. Any changes in environments and behaviours should be reflected in changing otolith chemistry, particularly in the first two years of life of juvenile snapper when they begin life in structured near shore environments and gradually move to more open waters. The Hauraki Gulf was, and is, a dynamic environment and fluctuations in Ba and Sr concentrations might be expected. However, a decrease of over 60 % for Ba in BS 2 between Occupation 1, 14th century, and Occupation 4/5, 18th century, would seem to be outside the expected range. To explain this we proposed that either volcanism associated with the Rangitoto volcano directly affected marine geochemistry in the gulf, elevating Ba levels; or that anthropogenic terrestrial landscape changes altered the hydrology of gulf waters and the balance between Ba concentrations and environments. While the latter seems more likely we cannot entirely rule out volcanism as an

explanation – we would have to repeat this research in a similar archaeological site in a similar environment that otherwise lacked a nearby active island volcano contemporaneous with human occupation. Anthropogenic causes seem a more parsimonious explanation. A 60 % decrease in Ba, however, does not indicate a 60 % change in other measurable environmental parameters. In fact, these environmental changes are likely to have been relatively subtle, with small shifts in freshwater inputs into the gulf waters and in the relationship between snapper transitional zones and fluvial mixing zones, which are no longer coincident in later occupations. These changes did not have any discernible impact on the movement patterns and behaviours of juvenile snapper. Pre-European Māori societies had no discernible impact on the snapper fishery, at least that our analytical methods can detect, and the fishery would have remained stable and productive throughout the sequence.

New Zealand has a short history, but this provides opportunities to examine pre-human and relatively unaltered early human environments. This study has offered valuable insights into the migration patterns of juvenile snapper, as well as the environmental factors that shape their early development. It has also provided a unique historical window into dynamic nature of the gulf and its changing characteristics since the arrival of humans in New Zealand.

CRedit authorship contribution statement

Matthew Campbell: Writing – original draft, Visualization, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Richard Walter:** Writing – review & editing, Conceptualization. **Louise Furey:** Writing – review & editing, Investigation, Funding acquisition. **Emma Ash:** Writing – review & editing, Investigation, Funding acquisition. **Andrew McAlister:** Writing – review & editing, Formal analysis. **Monica Tromp:** Writing – review & editing, Investigation. **Malcolm Reid:** Writing – review & editing, Methodology, Investigation. **Jingjing Zhang:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Michelle Simone:** Writing – review & editing, Methodology. **Julian Lilkendey:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Lindsey White:** Writing – review & editing, Funding acquisition. **Armagan Sabetian:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

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Data availability

data is publicly available on figshare

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