



Historical analyses of coastal marine sediments reveal land-based impacts on the benthos

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Abstract: We document from a sediment core collected at 23 m water depth offshore of Separation Point on the northern coast of Aotearoa New Zealand's South Island, 3000 years of natural and human-induced change to undisturbed offshore sediments that are protected from contact fishing methods. Multivariate analysis of sediment characteristics and sources of primary productivity successfully differentiated the pre-human (< 1500 AD), Māori, and European periods (> 1850). Pre-human sediments were characterised by elevated proportions of shell gravels, reduced carbonate content and low sediment accumulation rates (SAR) (0.19–0.22 mm yr⁻¹). Māori period sediments were identified by presence of bracken-fern spores and higher levels of pelagic diatom than benthic production, higher proportions of silt, and a four-fold increase in SAR (0.86 mm yr⁻¹). European-influenced sediments containing introduced pine pollen were deposited at ca. 11 times pre-human rates (2.5 mm yr⁻¹) and contained the greatest proportions of clay and organic material. Two pre-human sediment samples that contained elevated pelagic diatom remains were misclassified by our analysis as Māori period samples and overlapped in time with known earthquake and palaeotsunami events, suggesting both disturbances have long-term effects on the ecology of diatoms. Changes to Māori period sediments were consistent with the use of fire, coastal land clearance for dwellings and modifications of soils for horticulture. These effects were later amplified by widespread land clearance for the development of pastoral farming and roading by Europeans.

Keywords: diatoms, Golden Bay, historical ecology, palaeoecology, palaeotsunami, sediment

Introduction

Coastal ecosystems in close proximity to human civilizations are highly modified globally, yet because of shifting baselines (Klein & Thurstan 2016), little is known about their 'benchmark' pre-human state (Saunders & Taffs 2009). This is especially true for soft sediment habitats (Snelgrove 1999; Halpern et al. 2007). Paleoecological analyses of soft sediment cores are important tools for establishing historical benchmarks to inform management, conservation and restoration of soft sediment and upstream habitats (Saunders & Taffs 2009; Dietl & Flessa 2011; Rick & Lockwood 2013). Aotearoa New Zealand (New Zealand) was one of the last large land masses to be colonised by humans and was transformed from a fully forested land-mass to one dominated by agriculture in less than ca. 800 years. This rapid and relatively recent change makes it globally important for studying historic and contemporary anthropogenic changes to land and the adjacent seabed.

New Zealand has been transformed by widespread anthropogenic land-use change; first by Māori via hunting, forest burning, and agriculture, and then by European settlement. By the time Europeans arrived in New Zealand, it is estimated that close to one half of the original forest had been removed by fire (Masters et al. 1957) with lowland and drier regions the most affected (McGlone 1983; 1989). European colonisation of New Zealand from the 1830's onwards greatly accelerated the rate of land-use change, with extensive clearance of forest, conversion of landscapes to farms and exotic forests, and then urban and industrial developments into the 21st Century (Park 1995; Norton & Miller 2000). As a result, sediment accretion accelerated over an order of magnitude in some coastal regions adjoining urban areas and steep erosion-prone farmlands (e.g. Hicks et al. 2011, Hughes et al. 2012); however, there is little known about the downstream and offshore consequences to the marine environment of pre- and post-human land-use change.

Diatoms have been frequently used to reconstruct historic

environmental conditions (e.g. Battarbee et al. 1999; Saunders & Taffs 2009; Smol & Stoermer 2010). As the siliceous frustules that diatoms produce can be preserved in sediments, they are good paleoecological indicators, especially because different components of diatom assemblages vary in response to changes in light intensity, temperature, salinity, nutrient availability, pH, and pollution (Birks et al. 1990; Battarbee et al. 1999; Duarte et al. 2000; Segal et al. 2006). For example, the morphology of diatom microfossils indicative of functional traits has been used to assess shifts in benthic versus pelagic dominance of primary production photic energy capture. Centric diatoms (diatoms with radial symmetry) are generally planktonic (floating) forms, whereas pennate diatoms (diatoms with bilateral symmetry) are generally benthic, littoral, or epiphytic, growing on, or attached to, the substratum (Cooper 1995a,b; Cooper et al. 2004). The ratio of centric to pennate diatoms (c:p) has thus been used to infer changes from benthic dominated to pelagic dominated assemblages (and vice versa), and as an indicator of eutrophication (Cooper & Brush 1993; Cooper 1995a; Andr n et al. 1999, 2000; Cooper et al. 2004). As consumers of both benthic and pelagic phytoplankton, coastal shellfish populations are integrally linked to the productivity of primary producers. Diatom fossil remains have been used as palaeo-environmental proxies in New Zealand to describe changes to lagoon and estuarine studies of tectonic and tsunami events (Ota et al. 1989, Clark et al. 2011, Goff & Chagu -Goff 2015), and diatom phytopigments used to describe productivity changes in Fiordland (Sch ller et al. 2015).

In the semi-sheltered waters of Tasman and Golden Bays (hereafter, Nelson Bays), extensive shellfish beds supported valuable dredge fisheries for three bivalve species; the greenshell mussel *Perna canaliculus*, the dredge oyster *Tiostrea chilensis*, and the scallop *Pecten novaezelandiae*, which at their peak had a combined value estimated at NZ\$90M y^{-1} (Michael et al. 2015). Historic reports of over-exploitation of mussel stocks as early as 1896 (Handley & Brown 2012), the more recent collapse of Nelson Bays shellfish fisheries, and various unexplained boom and bust cycles (Drummond 1994), have suggested a link with the historic and contemporary role of anthropogenic stressors including fishing methods and sedimentation (Michael et al. 2015). As benthic and pelagic phytoplankton capture euphotic energy at the base of coastal food webs, an understanding of pre- and post-human diatom communities and sediment structure should provide a valuable benchmark of ecosystem responses to large perturbations and cumulative anthropogenic effects over time. However, due to the widespread use of bottom contact fishing methods that homogenise sediments (Thrush et al. 2006; Handley et al. 2014), most coastal soft sediments are affected by contemporary effects of trawling or dredging. Our study site was chosen because the offshore sediments remain undisturbed because a 146 km² sector of the seabed directly offshore from Separation Point was granted protection in December 1980, before the development of modern robust synthetic fishing nets (Bradstock & Gordon 1983; Handley et al. 2014) (Fig. 1). Those restrictions were imposed to protect an area of robust bryozoan

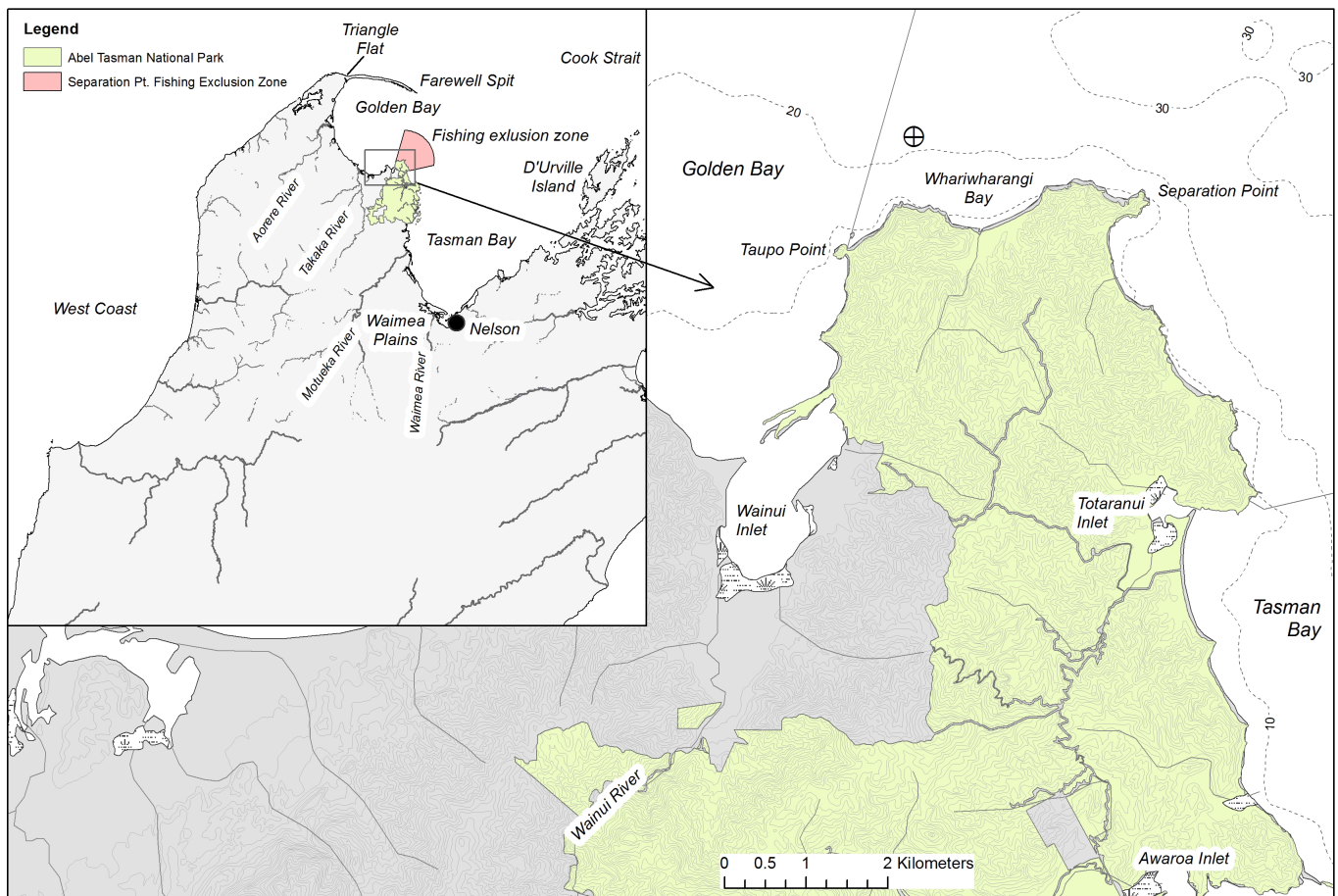


Figure 1. Location of the coring site (crossed circle) offshore from Whariwharangi Bay. Inset: location of coring site, Separation Point (WGS84: 40° 46.591 S, 172° 57.883 E), between Golden and Tasman Bays, in the north of Aotearoa New Zealand's South Island, indicating the Separation Point power-fishing exclusion zone, and Abel Tasman National Park.

Celleporaria agglutinans habitat perceived to be important recruitment habitat for fishes (Mace 1981; Bradstock & Gordon 1983). The aim of this study was to test the hypothesis that anthropogenic terrestrial disturbance, initiated by Māori and later accelerated by Europeans, caused changes to offshore sediment accumulation rates (SAR), sediment composition, and sources of coastal primary productivity.

Methods

Study site, geomorphology, hydrodynamics and history of human habitation

Separation Point is situated at the northernmost point of Abel Tasman National Park, New Zealand's smallest National Park, which was established in 1942 (Fig. 1). The park consists of 24 500 ha of intact and regenerating coastal forest atop Separation Point granite of Cretaceous age with localised Oligocene limestone outcrops (Grindley 1971; Goff & Chagué-Goff 1999). The seabed within the protected 'exclusion zone' slopes consistently (1–2°) away from the coastline out to the 20–22 m contours from where the seabed shelves gently (0.2–0.3°) moving into the deeper waters of Golden Bay (Land Information New Zealand, HS20–Abel Tasman Hydrographic Survey held by NIWA). The sediments include a relict, poorly sorted heterogeneous matrix of mud, sand and mollusc shell (Handley et al. 2014) that is sheltered from westerly swells by Farewell Spit (Fig. 1).

The biggest contributor to the average annual suspended sediment load to Tasman and Golden Bays is the Motueka River (41% of the total load delivered to the bays), with significant contributions from Waimea (13%), Aorere (12%), Wainui (9%), and Takaka catchments (8%) (Hicks et al. 2011). Mean and maximum wave height ca. 12 km north of Whariwharangi Bay were estimated to be 0.62 and 1.65 m respectively (Zeldis et al. 2011). A simulated depth-averaged circulation model indicates a small (< 2 cm s⁻¹) residual north-easterly tidal current off Whariwharangi Bay (Tuckey et al. 2006). Under large flood conditions, the Motueka River plume can extend into Golden Bay, and considerable amounts of sediment are also delivered to Golden Bay by the Aorere River and to a lesser extent Takaka River. The sediments offshore from Whariwharangi Bay comprise sandy muds, with moderate (ca. 20%) gravel component (Bostock et al. 2019).

Māori occupation of the Abel Tasman National Park area spanned some 500 years, with Māori archaeological horizons in Golden Bay dated from the sixteenth century but are possibly as old as the fifteenth century (Smith 1997; Barber 2013). Archaeological data indicate a mobile lifestyle based on fishing, hunter-gathering and horticulture (Anderson & Smith 1996). Whariwharangi Bay (Fig. 1) was a significant garden site for Māori, and Taupo Point was a defence (pā) site (Smith 1997; Furey 2006). European settlement of Nelson began in the 1840's with surveys of the Abel Tasman coastline beginning in 1854. Land purchases followed with 1000 acres sold between Totaranui and Wainui, including Separation Point, and a grazing licence issued for 6000 acres reaching to the Awaroa Inlet. Between 1901 and 1917 approximately 1000 acres of forest was cleared in Wainui Inlet to develop pasture. By the 1930's hill farmers in Wainui abandoned their land as soil fertility and economic conditions declined (Smith 1997). Although Abel Tasman National Park was established in 1942, it was not until 1977 that the land between Whariwharangi to Wainui Inlet, inshore of our coring site, was included in the

National Park. Pastureland in this area has since reverted to native forest and shrubland.

Core collection and sampling

A custom-built, variable frequency, vibra-corer was used to collect a 130 cm × 100 mm core from 23 m depth of water 1.4 km offshore from Whariwharangi Bay (Fig. 1) using SCUBA in May 2010. This core was divided into 5 cm depth increments that were sampled for sediment grain size, diatoms, pollen and stable isotope analyses. An additional 10 cm short core was hand-collected to obtain undisturbed surface sediments.

Dating, palynology and diatom analyses

Sediment geochronology was established via pollen/spore analysis and radiocarbon (¹⁴C) isotopic analysis of bivalve shells from the long core. Samples were prepared for pollen/spore analysis by the standard acetolysis method (Moore et al. 1991). Accelerator Mass Spectrometry (AMS) dating of ¹⁴C was carried out on two suspension-feeding *Dosinia* sp. shells from 120 and 125 cm sediment core depths by the University of Waikato, RadioCarbon Dating Laboratory. The shell surfaces were first cleaned, washed in an ultrasonic bath, tested for recrystallization of aragonite, and acid washed using 0.1N HCl. Results are presented as Conventional age of Percent Modern Carbon (pMC) following Stuiver and Polach (1977). This is based on the Libby half-life of 5568 yr corrected for isotopic fractionation. The ¹⁴C dates were calibrated using OxCal v4.3.2 (Ramsey 2017), the Marine13 calibration curve (Reimer et al. 2013) with a marine reservoir correction of -7 ± 45, that incorporates all New Zealand values (Petchey et al. 2008, F Petchey pers. comm.). Calibrated ages are reported as 95.4% confidence ages as cal BP years or AD equivalents when comparing dates with other studies.

Disturbance on adjacent land, first by Māori and subsequently by European settlers, was identified by spore and pollen analyses of sub-samples (1–2 cm³) from 5 cm slices of the long core and 1 cm slices of the top 5 cm of the short core. The colonisation of the adjacent land by Māori was identified by the presence of spores of bracken fern (*Pteridium esculentum*) Bracken is an invasive, indigenous ground fern with widely dispersed spores, common in New Zealand pollen spectra since human settlement and almost always associated with large-scale repeated burning of forest by early and latter Māori (McGlone et al. 2005). The presence or absence of European-introduced pine (*Pinus radiata*) pollen identified samples as European or pre-European respectively (McWethy et al. 2009, Clark et al. 2011). Initially, the whole slide from each sample was scanned for indicators of human activity and recorded as presence/absence. For slides containing human introduced species, a total of two hundred pollen grains and spores were counted in alternate 10 cm intervals once established as being present in lower core slices. Sediment accumulation rates were calculated from the above date estimates for the pre-human, Māori, and European periods by dividing the core section lengths by the presumed number of years represented in each length. Date ranges for the pre-human SAR were calculated from the average of the two ¹⁴C shell dates to the first presence of bracken spores.

Samples were prepared for diatom analysis using the standard biosilicate concentration method of density separation (2.3 specific gravity) with sodium polytungstate (Piperno 2006). In the upper deposits, where diatoms were reasonably well concentrated, at least 200 individuals (or fragments thereof) were counted from each sample collected from the 5 cm slices

from the long core. Below 35 cm depth, diatoms became progressively rarer, so 100 frustules were counted down to 120 cm and 50 frustules at the 125 cm level. Interpretation of the c:p diatom ratio were analysed under the assumption that the preservation of diatom frustules did not differ between the two groups over time.

Sediment grain size and lithology

Grain size analysis was carried out for pre-weighed dry samples that were first wet sieved to 1 mm to remove coarse sands and shell-gravels and then sieved to extract the 62.5 μm fractions for silt, before drying and weighing. The > 1 mm and < 62.5 μm fractions were digested with 10% HCl, dried, and reweighed to establish the carbonate fraction of each sample. From the < 62.5 μm samples, a 2 mg sample was sub-sampled for stable isotope analysis (below) before organic content was removed by oxidation with H_2O_2 at 80°C (Vaasma 2008) and the sample was dried and re-weighed to quantify organic content. For laser size analysis, a 5 g sub-sample of the < 1 mm fraction was dispersed in 60 ml of 50 g L^{-1} hexametaphosphate solution for a few hours and sonicated for 10 seconds using a Cole-Parmer 8891 ultra-sonicating bath. Particle size analysis was conducted using a Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyser and these results were entered into GRADISTAT Version 6.0 grain size analysis software to estimate particle size distributions (Blott & Pye 2001).

Isotope analysis

Stable isotope analyses of sediment samples were carried out on a DELTA^{plus} isotope ratio mass spectrometer (Thermo Fisher Scientific, Bremen, Germany). Solid samples were prepared in tin boats and combusted in an NA 1500 elemental analyser with an AS200_LS autosampler (Fisons Instruments, Rodano, Italy) at 1020°C in a flow of oxygen and He carrier gas. Oxides of N were reduced to N_2 gas in a reduction furnace at 640 °C. N_2 and CO_2 gases were separated on a Poropak Q gas chromatograph column before being introduced to the mass spectrometer detector via an open split. CO_2 and N_2 reference gas standards were introduced to the mass spectrometer with every sample run. ISODAT software calculated $\delta^{15}\text{N}$ values against atmospheric air, and $\delta^{13}\text{C}$ values against the CO_2 reference gas relative to the international standard Carrara Marble NSB-19 (National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA). This, in turn, was calibrated against the original Pee Dee Belemnite (PDB) limestone standard and was then corrected for ^{17}O . Carbon isotope data were normalised using National Institute of Standards and Technology (NIST) 8573 (USGS40 L-glutamic acid; certified $\delta^{13}\text{C} = -26.39 \pm 0.09\text{‰}$), NIST 8574 (USGS41 L-glutamic acid; certified $\delta^{13}\text{C} = 37.63 \pm 0.10\text{‰}$), NIST 8541 (USGS24 graphite; certified $\delta^{13}\text{C} = -16.05 \pm 0.07\text{‰}$ and NIST 8542 (IAEA-CH-6 sucrose; certified $\delta^{13}\text{C} = -10.45 \pm 0.07\text{‰}$). Nitrogen isotope data were normalised using NIST 8573 (USGS40 L-glutamic acid; certified $\delta^{15}\text{N} = -4.52 \pm 0.12\text{‰}$), NIST 8574 (USGS41 L-glutamic acid; certified $\delta^{15}\text{N} = 47.57 \pm 0.22\text{‰}$), NIST 8547 (IAEA-N-1 ammonium sulphate; certified $\delta^{15}\text{N} = 0.43 \pm 0.04\text{‰}$) and NIST 8548 (IAEA-N-2 ammonium sulphate; certified $\delta^{15}\text{N} = 20.41 \pm 0.2\text{‰}$). A laboratory standard, DL-Leucine (DL-2-Amino-4-methylpentanoic acid, $\text{C}_6\text{H}_{13}\text{NO}_2$, Lot 127H1084, Sigma, Australia), was run every ten samples to check analytical precision and enable drift corrections to be made if necessary. Repeat analysis of standards produced data accurate to within

0.25‰ for both $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, and a precision (1 SD) of better than 0.10‰ for $\delta^{15}\text{N}$ and 0.21‰ for $\delta^{13}\text{C}$.

Statistical analyses

We sought to determine if sediment properties differed among three time periods: pre-human (earlier than 1500), Māori (1500–1849), and European (1850–2010). To visualise graphically the underlying patterns in the data, a Euclidian distance resemblance matrix was created among samples for the data: diatom ratios, isotope ratios ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), and sediment variables (% shell gravel, % sand, % silt, % clay, % colloid, % carbonate, and % organic material), and then the constrained ordination method of canonical analysis of principal coordinates (CAP; Anderson & Willis 2003) was used to find axes through the multivariate cloud that best discriminated among time periods. A cross validation procedure (leave-one-out allocation of observations to groups) was used to estimate the misclassification rate of samples among periods (Fielding 2006). To investigate potential drivers of variability within the dataset, Spearman's correlations of sediment and diatom variables with the canonical axes were plotted as vector overlays.

Results

Dating and palynology

The two shells found as disarticulated valves from 120 (*Wk-28099*) and 125 cm (*Wk-28107*) cores were aged at 2735–2990 calBP and 2834–3149 calBP respectively. Pollen indicators of vegetation disturbance by humans were not found in the lower section of the 130 cm core, indicating that deposition occurred before human settlement of the region. The first clear evidence of initial, large scale human impact on the landscape, indicated by bracken fern spores, appeared at 70 cm depth (Fig. 2a). As midden ^{14}C dates from excavations in Golden Bay date to 1500 AD (Smith 1997; Barber 2013), this can be considered the probable maximum age for that depth. The presence of pine pollen associated with European settlement, appeared at 40 cm depth in the first scan of that slide, but not in the latter count. Pine was naturalised in parts of New Zealand by 1830, but European settlement on the Abel Tasman coast didn't occur until the 1850's (Smith 1997): this was therefore considered a probable maximum age for that depth. Pine pollen was found throughout upper core layers.

Univariate sediment characteristics

Estimates of SAR calculated for the date of each of the two AMS dates from the *Dosinia* shells to the presence of bracken spores, were 0.197–0.219 and 0.204–0.231 mm y^{-1} . Unmodified sediments contained the lowest proportions of carbonate, organic and clay content (Fig. 2b). During the Māori period, SAR increased by a factor of approximately four (1500–1850: 0.91 mm y^{-1}). Percent carbonate continued to increase, and silt content fluctuated with some peaks in the mid to late Māori period. There was also an increase in $\delta^{13}\text{C}$ values and elevated pelagic diatom production during that time. Following European colonisation, $\delta^{13}\text{C}$ values decreased with corresponding decrease in shell gravels and carbonate, consistent with increasing proportions of silt, clay and organic content. The SAR for the combined effects of Māori and Europeans since 1850 exceeded pre-human deposition rates by an order of magnitude (ca. 2.8 mm y^{-1}). Following the

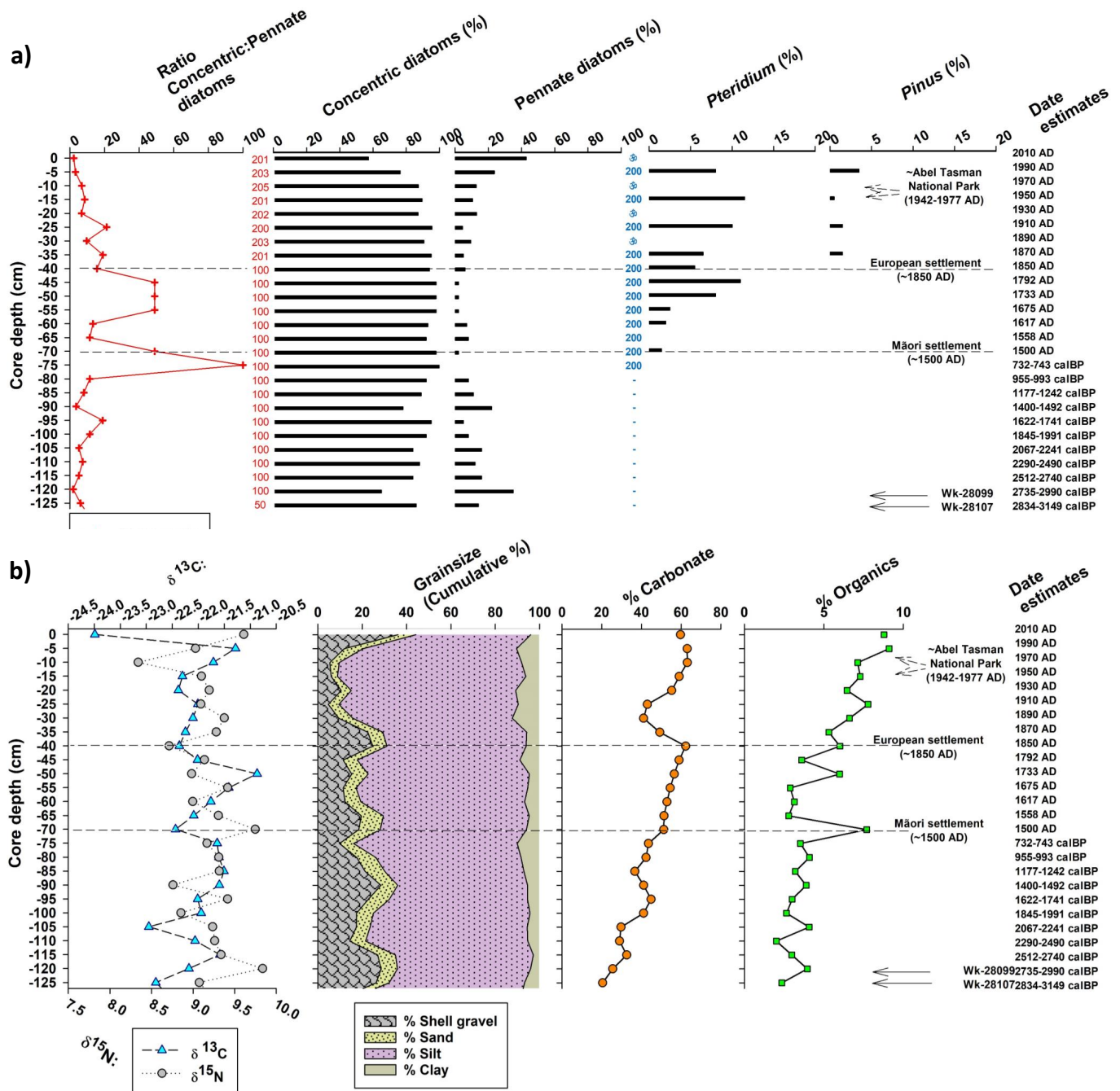


Figure 2. Core stratigraphy from sediment cores collected from Whariwharangi Bay, Nelson (Aotearoa New Zealand) including: (a) concentric to pennate diatom ratio; and percent diatoms, bracken spores and pine pollen (⊕ identified during scan of all slides, – absent during scan of all slides, + found as present in scan of slide, but absent in 200 count), (b) Sediment accumulation rates derived from the presence of bracken spores (Māori) and pine pollen (European) and ^{14}C dating of shells were used to estimate dates of 5 cm slices. B $\delta^{13}C$ and $\delta^{15}N$ isotope ratios, cumulative grainsize; % carbonate content and organic content.

establishment of the Abel Tasman National Park in the later part of the European period, diatom production became dominated by benthic pennate species, shell gravel content increased, and proportions of silt and clay diminished towards the sediment surface. Carbon and nitrogen isotopic ratios showed various fluctuations that were sometimes synchronous with other variables, but generally difficult to interpret.

Multivariate analysis

The CAP analysis correctly classified 23 of the 26 samples (88.5%) to their time-periods of origin (Fig. 3). The three

misclassified samples were from 60, 75 and 95 cm. The pre-human and Māori sediments were separated along the CAP2 axis whereas the European samples were separated along the CAP1 axis. Pre-human sediments were positively correlated with higher shell gravels and carbonate content, while higher silt levels were positively correlated with European-modified samples. The Māori period was correlated with lower concentrations of pennate benthic diatoms (decreased c:p ratio), and European sediments were correlated with higher clay and organic content.

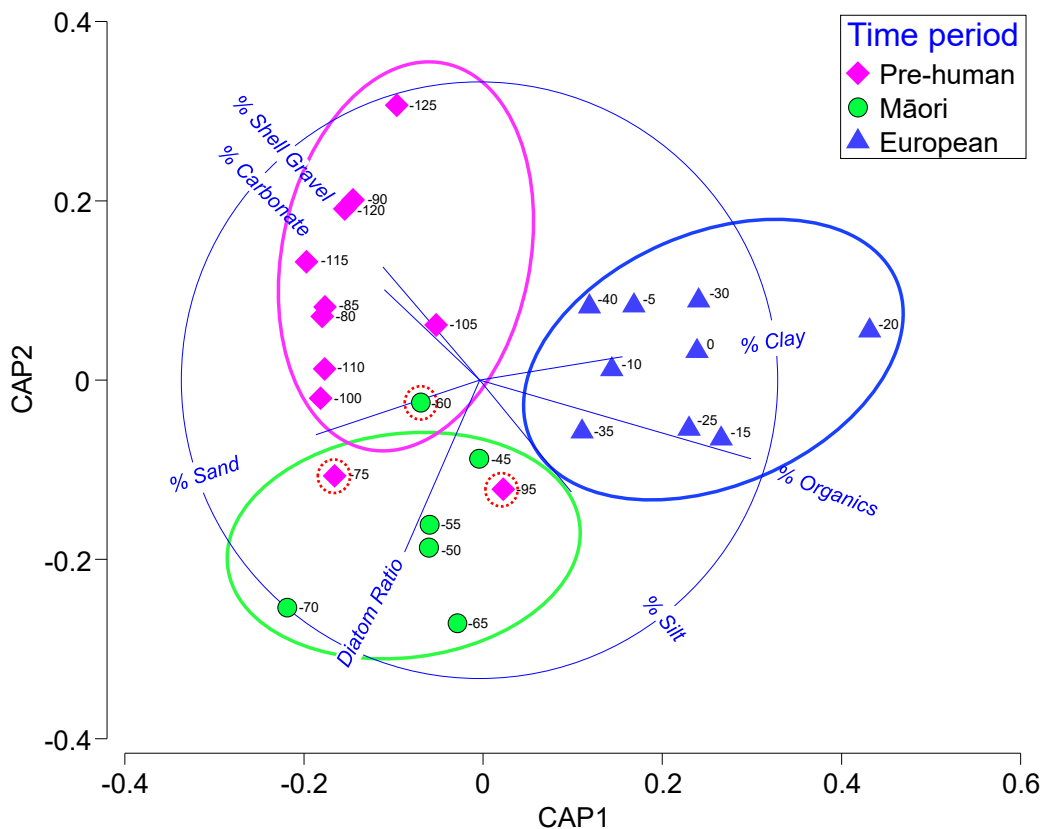


Figure 3. Canonical Analysis of Principal coordinates discriminating time periods of core sections identified by pollen, spore and ^{14}C analyses. This constrained ordination is based on the Euclidean distance measure computed on standardised variables. Samples are labelled numerically by depth, colour-coded by time period, and misclassified samples are highlighted by dashed circles. Spearman correlation > 0.4 of sediment characteristics are superimposed: their lengths and directions show correlations with the ordination.

For later discussion of misallocated samples in the CAP analysis, approximate dates of each 5 cm slice were calculated from SAR estimates (Fig. 2), under the assumption that sediment accumulation rates were constant within each time-period.

Discussion

Our results record, in Nelson Bays, anthropogenic signatures in offshore sediments demonstrating historical effects from colonisation by Māori, with the combined effects of colonisation by Europeans, who developed pastoral farming inland from our protected site in Nelson Bays. Māori period marine sediments were correlated with higher silt loads and an increase in the proportion of pelagic diatom production. These findings suggest that acceleration of fine sediment led to a four-fold increase in SAR and smothered benthic diatoms or provided nutrients for pelagic diatom productivity offshore from Whariwharangi Bay. During the European period, SARs increased by a further order of magnitude, depositing sediments containing higher proportions of clay and organic content, reduced sand content and variable carbonate deposition. This contrasts with a study of two inland Hawke's Bay lakes that showed only minor (1.5–1.6%) acceleration of sediment accumulation during Māori occupation, as compared with 6–8 times faster during European occupation (Wilmschurst 1997). The authors attributed the increased rates of erosion in the Lake Tutira catchment to

the large size of the catchment, the rapid period of deforestation, the steep hillslopes and many streams. Another study from the North Island that compared a Waipaoa catchment swamp core with a marine core taken on the shelf in Poverty Bay (63 m water depth) showed similarities in regional scale disturbances detected from similar pollen and spore profiles (Wilmschurst et al. 1999). They noted from their terrestrial core a dramatic increase in the amount of soil eroded into the Repongaere swamp after Māori deforestation. However, in contrast to poor evidence of erosion from the terrestrial core, the marine core captured an order of magnitude increase in sedimentation after conversion of remaining forest and Māori induced fern/scrub into pasture by Europeans.

The increase in clay content early in the European period was most likely associated with development of cattle and dairy farming and construction of bridle-tracks and roading to service the pastoral farms that were developed within the various bays on the Abel Tasman peninsula and further afield. Corroborating our results, Goff & Chagué-Goff (1999) observed a peak in organics and silt in Wainui Inlet between 1338–1478 AD coincident with Māori settlement and increases in clay content following European settlement. Their pre-European SAR was estimated at $0.5\text{--}1.7\text{ mm y}^{-1}$, Māori sedimentation rates were $0.98\text{--}1.19\text{ mm y}^{-1}$ compared with post-European settlement rates of $1.6\text{--}2.7\text{ mm y}^{-1}$ increasing to modern rates of $2.3\text{--}3.3\text{ mm y}^{-1}$. These rates are comparable to our SARs except for much lower rates estimated in pre-human times in our offshore core. As the *Dosinia* shells we had ^{14}C dated

were discovered disarticulated, we acknowledge there may be a degree of additional uncertainty present in our pre-human chronology because in the semi-sheltered coastal setting, there is potential that such shells may have been reworked during taphonomic processes (Kidwell & Bosence 1991). This could mean that the shell depositional depths may have been younger than their death horizons, if for example they were repeatedly brought to the sediment surface during mixing by large storms or bioturbation. However, such events would likely lead to an underestimate of our pre-human SAR. Nevertheless, countering any underestimates are potential coastal inundations by palaeotsunami (Chagué-Goff & Goff 1999; Goff & Chagué-Goff 1999) that could have potentially increased the pre-human SAR estimate to an unknown extent. The potential causes of the increase in the proportion of carbonate during Māori and latter European periods are unclear. Although shellfish production may have increased because of greater supply of nutrients and pelagic diatom production following human habitation, the burial and preservation of shells through taphonomic processes can be influenced by a suite of biological, physical and chemical processes. All these however would be affected by the net increase in seafloor aggradation – with the potential periodic catastrophic burial from storm or tsunami events (McKnight 1969), and the pervasive effects of accelerated SARs reducing the time post-mortem shells were exposed to taphonomic processes (Kidwell & Bosence 1991).

We propose that Nelson Bays' water column diatom communities appeared to respond to terrestrial discharge of nutrients produced during the latter Māori period. The initial increase in sedimentation from land clearance likely smothered and shaded benthic diatoms, but with the continued use of fire and gardening activities nutrient discharge from the catchment likely increased. Analysis of over 1000 acres of lowland soils known to have been cultivated by pre-European Māori on the nearby Waimea Plains showed them to contain high proportions of charcoal, demonstrating that local Māori used fire as an important tool in horticulture, along with the addition of large quantities of fine gravel and coarse sand dug from pits up to six feet deep, making the soil free draining and easy to cultivate (Rigg & Bruce 1923). The black-coloured soil contained considerable quantities of charcoal sourced from burning forest and regenerating species, especially manuka (*Leptospermum ericoides*), which was thought to serve two purposes: that of heat absorption, and regulation of soil acidity due to their high phosphoric acid and potash content. It was estimated that several hundred tons of vegetable matter were burnt on each acre (Rigg & Bruce 1923). A recent global-scale meta-analysis of effects of fire, showed that affected soils contain elevated levels of phosphorous with lower ratios of phosphorus:carbon and phosphorus:nitrogen content (Butler et al. 2018) and significant increases in soluble ammonium (NH_4^+) (94%) and nitrate (NO_3^-) (152%) (Wan et al. 2001).

In this study, we saw no evidence of an abrupt regime shift from benthic to pelagic diatom production following human habitation. A 2500 yr historical reconstruction from Chesapeake Bay sediments (Cooper & Brush 1993; Cooper 1995a,b) reported declining diatom diversity, and dramatically increasing ratios of c:p diatoms in sediments responding to eutrophication from increasing anthropogenic effects. Similarly, a reconstruction of palaeo-primary productivity in New Bedford Harbour in Boston found that before European settlement estuarine production was benthic dominated but switched to greater pelagic production following cumulative impacts that started with forestry clearance, urbanisation

and discharge of sewage, culminating in changes to harbour hydrography (Spasojević 2002; Chmura et al. 2004). In our study, pelagic diatom production fluctuated during early European period, with a small peak around 1910, consistent with nearby forests in Wainui Inlet being burned and cleared for cattle farming (Smith 1997). Wilmshurst et al. (1999) noted an increase in *Typha orientalis* and *Urtica* pollen, which they attributed to a response to elevated levels of nutrients released after land clearance in their Gisborne study. In cores collected in the Mahurangi Harbour, which were more analogous to ours being from a sheltered coastal setting, Grenfell et al. (2007) implicated increased abundance of large diatoms, including the centric species *Paralia sulcata*, to elevated nutrients associated with the increased sediment and freshwater runoff, rather than oyster farm input.

The two pre-human samples that were misclassified as Māori in our CAP analysis (both showing decreases in pennate diatom counts), coincided with date estimates of palaeotsunami striking the Abel Tasman Peninsula. The 75 cm sediments [c. 1500–1207 AD / 743 cal BP] overlapped with the combined palaeotsunamis: c. 1440 AD and c. 1220 AD (Goff & Chagué-Goff 1999). We speculate that coastal inundation by both those palaeotsunamis ca. 200 years apart, would have caused significant pulses of sediment, likely shading out and smothering benthic diatoms and/or releasing nutrients enhancing pelagic diatom production. The 95 cm layer [c. 1492–1741 cal BP], that had a smaller peak in pelagic diatoms, also coincides with another less distinct palaeotsunami signature recorded from Wainui Inlet in c. 1600 yr BP (Goff & Chagué-Goff 1999) consistent with the Taupo eruption (1718 ± 5 cal. BP: Hogg et al. 2011). The misclassification of those two samples as Māori period sediments, indicates they were consistent in properties created during a period of terrestrial disturbance, and if created by palaeotsunami, the alignment of those events supports our dating estimates. We note however, that there have been 32 tsunami events recorded around New Zealand between 1840–1982 (De Lange & Healy 1986), that have not produced large sedimentological/diatom responses commensurate with those in our core. Goff & Chagué-Goff (1999) found only minor evidence suggestive of tsunami signatures from the largest 1855 event in Abel Tasman estuaries since Europeans arrived, but they did not use diatoms in that study, which are acknowledged in a subsequent review as useful proxies (Chagué-Goff et al. 2011). In a tectonically active continent such as New Zealand, the apparent dynamic nature of sedimentary processes that incorporate large storm events, earthquakes and tsunamis, shows that pre-human 'benchmark' sediment conditions may not represent a static stable state.

The importance of providing an historic baseline to contextualise modern changes to marine systems that support ecologically and economically important biota, including shellfish, can be seen at several levels in this study. First, our results illustrate changes in the magnitude and compositional changes to offshore sediments, with increasing rates of deposition delivering more silt and organic loads associated with first coloniser Māori, a process greatly accelerated following European colonisation, especially with the advent of pastoral farming. Second, sediments during the Maori period—when Maori occupied and developed low-lying coastal areas—clustered with sediments consistent with timing of tsunami. These findings support the deduction that the coastal fringe discharged elevated levels of silt and organic material in response to humans and tsunami alike.

We propose that there are likely links with the cumulative

effects of increasing proportions of organic material and large pulses of silt and clay into Nelson Bays over decadal to century time-scales, some from natural events, and an increasing proportion from anthropogenic effects. As the resuspension of increasing levels of fine sediments was one of several theories put forward explaining the lack of innate recovery of Nelson Bays' shellfish beds (Michael et al. 2015), the increasing SARs with larger quantities of fine silts and clays in our core show that shellfish decline may, in part, be due to an historic legacy effect. Effective rehabilitation of nearshore marine habitats is however not decoupled from catchment-scale land use, and successful management of coastal fisheries and habitats will require a wider range of management action than has previously been employed. To inform the restoration of shellfish beds in Nelson Bays, we recommend that future studies should include comparisons of sediments inside and outside the fishing exclusion zone to attempt to disentangle contemporary effects of fishing disturbance from legacy and recent effects of sedimentation.

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