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RESOLVING UNCERTAINTIES IN FORAMINIFERA-BASED RELATIVE SEA-LEVEL RECONSTRUCTION: A CASE STUDY FROM SOUTHERN NEW ZEALAND

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ABSTRACT

Since the pioneering work of David Scott and others in the 1970s and 1980s, foraminifera have been used to develop precise sea-level reconstructions from salt marshes around the world. In New Zealand, reconstructions feature rapid rates of sea-level rise during the early to mid-20th century. Here, we test whether infaunality, taphonomy, and sediment compaction influence these reconstructions. We find that surface (0–1 cm) and subsurface (3–4 cm) foraminiferal assemblages show a high degree of similarity. A landward shift in assemblage zones is consistent with recent sea-level rise and transgression. Changes associated with infaunality and taphonomy do not affect transfer function-based sea-level reconstructions. Applying a geotechnical modelling approach to the core from which sea-level changes were reconstructed, we demonstrate compaction is also negligible, resulting in maximum post-depositional lowering of 2.5 mm. We conclude that salt-marsh foraminifera are indeed highly accurate and precise indicators of past sea levels.

INTRODUCTION

The pioneering work by David Scott, to whom this volume is dedicated, on the use of salt-marsh foraminifera in Nova Scotia and California for reconstructing Holocene sea-level changes (Scott, 1977; Scott & Medioli, 1978, 1980, 1986) instigated four decades of sea-level studies from all over the world including some from the Southern Hemisphere. In New Zealand, where Scott worked in the late 1990s (Hayward et al., 1999), reconstructions show that the rate of recent (20th century) sea-level rise was anomalously rapid compared both to late Holocene rates and also rates recorded by Northern Hemisphere salt marshes during the same time interval (Gehrels et al., 2008; Garrett et al., 2022). This has led to some speculation about these discrepancies; are they real and indicative of regional dynamics in sea-level processes, or are there local processes at play that could throw the reliability of proxy sea-level records into question (Fadil et al., 2013)? While some uncertainties, such as the vertical range over which a particular assemblage of foraminifera might be expected to be encountered, are explicitly accounted for, other processes are sometimes only cursorily mentioned or entirely overlooked. In this study we assess the significance of two such processes: post-depositional changes due to infaunality and taphonomy and sediment compaction. These processes, if significant, could result in flawed sea-level reconstructions.

While the quantitative sea-level reconstruction approach is predicated on surface and fossil samples being compositionally similar, fossil assemblages, unlike their modern counterparts, are the product of both test production at the surface and by species living infaunally (Goldstein & Harben, 1993; Hippensteel et al., 2000; Tobin et al., 2005; Hayward et al., 2014; Chen et al., 2020). Post-mortem taphonomy may also result in fossil assemblages that differ from modern samples, introducing further uncertainty (Goldstein & Watkins, 1999; Berkeley et al., 2007). Potential taphonomic processes include mechanical breakage and abrasion, bioerosion, oxidation of organic cements, and dissolution (Goldstein & Watkins, 1999; Berkeley et al., 2007). Both infaunal test production and taphonomic alteration have the potential to result in the formation of foraminiferal assemblages (thanatocoenoses) that are dissimilar to the surface samples that are employed to model species' distributions along the elevation gradient. Predictions based on these surface samples may, therefore, not accurately match the true depositional elevation of fossil samples.

In this paper, we build on previous investigations into infaunality and taphonomy by investigating a sample set consisting of paired surface (0–1 cm depth) and shallow subsurface (3–4 cm depth) samples from a salt marsh in southern New Zealand from which a high-resolution late-Holocene relative sea-level (RSL) record has recently been derived (Garrett et al., 2022). We investigate spatial variability in the differences between surface and subsurface assemblages in this novel sample set and seek to identify how environmental change, infaunality, and early-stage (years to decades) taphonomic loss of specimens biases final assemblages. We assess the potential for these processes to bias or introduce additional uncertainty into RSL reconstructions. While this sampling strategy precludes a full depth-integrated analysis of infaunality and taphonomy (cf. Tobin et al., 2005; Chen et al., 2020), it does provide a unique spatial view of these processes.

Alongside our assessment of infaunality and taphonomic alteration, we address the role of sediment compaction as a further source of uncertainty in relative sea-level reconstructions. Sediment compaction lowers foraminifera-bearing sediments from the elevation at which they were originally deposited, potentially resulting in overestimation of the rate of RSL rise (Allen, 2000; Brain et al., 2011, 2012). Due to their highly organic nature, the high marsh-sediments favoured for foraminifera-based RSL reconstruc-

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tions may be more susceptible to compaction than more minerogenic sediments found lower in the tidal frame (Brain, 2015). Regional estimates of rates of sediment compaction can be obtained from sea-level databases (e.g., Horton & Shennan, 2009), but are dependent on the presence of basal peats that rest directly on an incompressible substrate (e.g., Törnqvist et al., 2008). These regional estimates of rates of compaction-driven post-depositional lowering of sea-level index points are averaged over centennial to millennial timescales and so lack sufficient resolution to be applicable to thinner sections of salt-marsh sediment used to reconstruct relative sea level of decadal to centennial and millennial timescales (e.g., Gehrels et al., 2001; Kemp et al., 2018). Geotechnical modelling has provided an alternative means of assessing the effects of compaction in single-core, high-resolution sea-level reconstruction. For example, modelling work by Brain et al. (2012) suggested that, compared to North Atlantic sequences, reconstructions of relative sea level from the thin high-marsh deposits overlying well-consolidated muds in Southern Hemisphere records are less prone to the effects of sediment compaction. However, the effects have not been previously quantified (Gehrels et al., 2008; Garrett et al., 2022); hence, we address this issue in more detail here.

STUDY SITE

We focus on the tidal marshes fringing the southern margin of Mokomoko Inlet, located close to the entrance of the New River Estuary, near the southern tip of New Zealand's South Island (Fig. 1). A number of characteristics make the site suitable for developing high-resolution RSL reconstructions for the last few centuries including its small tidal range [mean sea level (MSL) to highest astronomical tide (HAT) range of 1.49 m], limited freshwater input, stable geomorphic setting, and the low likelihood of past changes in tidal range. The southern coast of the South Island is also generally considered one of the most tectonically stable regions of New Zealand over multi-millennial timescales (Beavan & Litchfield, 2012), although vertical land motions over shorter timescales are less well resolved (Garrett et al., 2022). The salt marshes fringing Mokomoko Inlet display clear zonation of vegetation, with *Apodasmia similis* found throughout low, mid, and high marsh environments, *Plagianthus divaricatus* in the mid and high marsh, and *Phormium tenax* in the high marsh only.

Garrett et al. (2022) described the zonation of foraminiferal assemblages in a transect of surface samples from Mokomoko Inlet, finding *Trochamminita* spp., *Haplophragmoides wilberti* and *Miliammina fusca* the dominant species in high, mid, and low marsh environments, respectively. The authors used this training set, along with previously reported assemblages from Pounawea (Southall et al., 2006), to develop regional transfer functions capable of predicting depositional elevations with decimetre-scale uncertainties from foraminifera preserved in a sediment core. The sediment core, MKT-18.5, was obtained from immediately adjacent to a 25-m-long trench that was used to map the stratigraphy of the site. The sedimentary sequence consists of peaty mud and organic sandy silt layers with a total thickness of between 0.3 and 0.6 m overlying subangular greywacke boulders, cobbles, and very coarse gravel sitting directly on in-situ greywacke rock. Assemblages preserved in MKT-18.5 are dominated by *Trochamminita salsa*, with *H. wilberti* encountered in increasing numbers towards the top of the core. Corresponding depositional elevation predictions indicate sediment accumulation close to HAT, with a ~10-cm decline in marsh-surface elevation at the top of the core (Garrett et al., 2022).

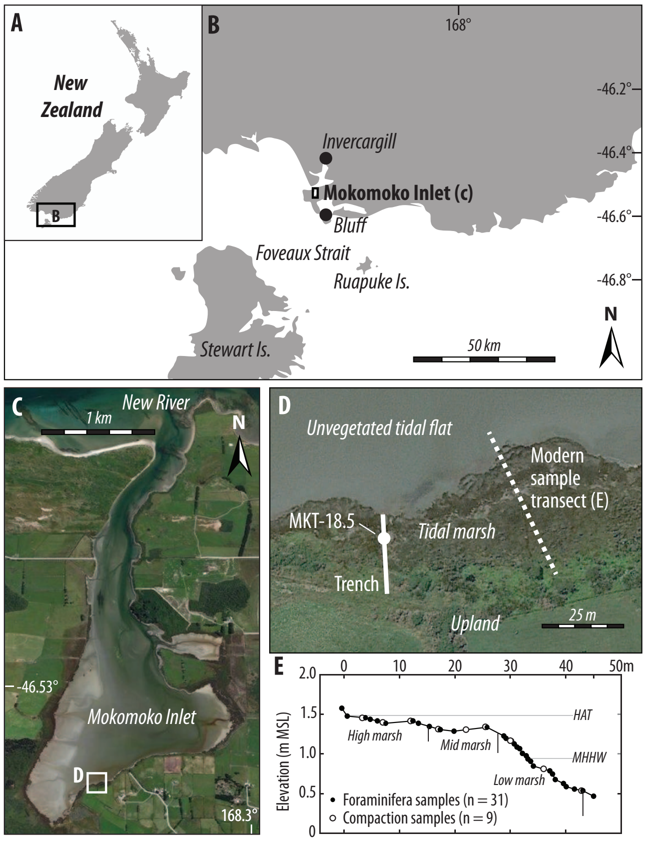

FIGURE 1. Location of the Mokomoko Inlet tidal marsh. Panel D shows the locations of the modern transect, the trench used by Garrett et al. (2022) to determine the stratigraphy, and the sampled core, MKT-18.5. Panel E shows the topography and the locations of the foraminifera and compaction samples along the transect. Highest astronomical tide (HAT) and mean higher high water (MHHW) are indicated. Aerial photos in panels C and D are from Bing Maps (https://www.bing.com/maps, image copyright DigitalGlobe, 2020).

METHODS

FORAMINIFERA SAMPLE COLLECTION

To assess the distribution of contemporary salt-marsh foraminifera at Mokomoko Inlet, Garrett et al. (2022) collected 31 surface samples along a 45-m-long transect ranging from the upper tidal flat to the lower limit of terrestrial vegetation (Fig. 1). We use these samples in this paper, alongside a novel set of co-located subsurface samples. Each surface sample consisted of the uppermost 1 cm of sediment, following a strategy widely employed in the sea-level literature (e.g., Scott & Medioli, 1978; Horton & Edwards, 2003; Williams et al., 2021). This sampling strategy seeks to minimize the impact of seasonal fluctuations in assemblages, whilst also ensuring that significant changes in sea-level have not occurred during sample accumulation. Nevertheless, this strategy neglects the potential contribution of infaunal species living deeper than 1 cm and taphonomic influences leading to post-depositional modification of assemblages (Goldstein & Harben, 1993; Hayward et al., 2014, 2015a; Chen et al., 2020). To investigate these processes, we recovered a corresponding subsurface sample from 3–4 cm depth at the location of every surface sample. We chose this depth as it lies within the zones of greatest infaunal presence and taphonomic activity identified at other sites in New Zealand (Hayward et al., 2015a). Furthermore, it provided a balance between samples that might be too young to have accumulated assemblage changes and deeper samples that might have been influenced by spatial differences in sedimentation rate and would, therefore, represent a more diachronous sample set.

Due to the lack of geodetic benchmarks or tidal observations from the site, sample elevations were ascertained by identifying the highest occurrence of foraminifera and relating this to HAT (following Gehrels et al., 2001; Charman et al., 2010; Wright et al., 2011). A site-specific prediction of HAT was derived from the TPXO8-Atlas global tidal model (Egbert & Erofeeva, 2010), benchmarked against time series from the two closest tide gauges. The tidal model closely matches the phase and amplitude of tidal observations from Puysegur Welcome Bay and Dunedin (Garrett et al., 2022) and the predicted MSL to HAT range of 1.49 m for Mokomoko Inlet is in close agreement with the 1.5 m range given by Todd (2007) for the New River Estuary Mouth.

Foraminiferal Analysis

To differentiate between living and dead foraminifera, we added a rose Bengal-ethanol solution to all surface and subsurface samples within 24 hours of collection (Walton, 1952). We sieved samples and retained the fraction between 63 and 500 μm. The surface samples were counted wet, while the subsurface samples were first dried in a 40°C oven following the standard methods of the University of Plymouth and Geomarine Research laboratories, respectively. We considered specimens to be living if multiple chambers were stained (cf. Figueira et al., 2012). A comparison of wet and dry counts in three samples indicated no significant differences in the abundance or diversity of assemblages, suggesting that drying samples did not reduce recognition of stained specimens or increase disintegration of more fragile species in these assemblages (Appendix, Fig. A1). Where possible, we counted all foraminifera (living and dead) until a minimum of 100 dead specimens per sample was reached. Some samples with low densities yielded lower counts, as described in the results. For consistency with Garrett et al. (2022) and following Kemp et al. (2020), we focus statistical analyses on samples with dead counts exceeding 30.

Species identifications follow Hayward & Hollis (1994), with nomenclature updated following Hayward et al. (2022). We group *Trochamminita irregularis* and *T. salsa* as *Trochamminita* spp. as they were not originally differentiated in the subsurface samples. Garrett et al. (2022) found that, due to the close similarity between the modern distributions of *T. salsa* and *T. irregularis*, grouping the species did not negatively impact on transfer function performance, with no change in r^2 between observed and predicted elevations. We note that this group may also include unidentified specimens of the recently recognised *Pseudotrochamminita malcolmi* (King, 2021).

To assess the similarity between paired surface and subsurface samples, we use similarity coefficients calculated using the Bray-Curtis distance metric in PAST version 4.11 (Hammer et al., 2001). We compare these coefficients with the 95th and 50th percentiles of the similarity coefficients between the modern samples.

Geotechnical Analysis and Modelling

To address the potential for compaction and post-depositional distortion of the Mokomoko Inlet sedimentary sequence, and to 'decompact' the relative sea-level record presented by Garrett et al. (2022), we used the geotechnical model of Brain et al. (2011, 2012). Further details of the sampling, preparation, and analysis approach are given by Brain (2015) and Brain et al. (2017). In summary, we first determined the geotechnical properties of modern sediments collected from Mokomoko Inlet using nine undisturbed sediment samples, three each from the high, middle, and low marsh (Fig. 1d, e). For each sample, we measured loss on ignition (LOI) using standard methods (e.g., Head, 2008) and particle density (G_s) by gas pycnometry. We calculated the voids ratio for each sample using the Height of Solids method (Head, 2008; Head & Epps, 2011). Second, we determined the compression behaviour of each sample using fixed-ring, front-loading oedometers (Head & Epps, 2011), providing estimates of the voids ratio at 1kPa (e_1), the recompression index (C_r), the compression index (C_c), and the compressive yield stress (σ'_y). Third, to apply the compression model to core MKT-18.5 (location in Fig. 1d, sediments described by Garrett et al., 2022) and quantify post-depositional lowering (PDL), we measured LOI and bulk density at every centimetre throughout the 0.51-m core. Using the observed empirical relationships between LOI and e_1, C_r, C_c, and G_s, we assigned compression properties to each layer in the core using a Monte Carlo framework (5000 iterations). In each model run, we estimated σ'_y by sampling from a continuous triangular distribution defined by the minimum, modal and maximum values measured in the surface geotechnical samples. Results from the full suite of model runs provided estimates (mean ± one standard deviation) of effective stress and PDL throughout the sediment core. Comparison of measured and model-predicted dry density provided an assessment of the predictive capacity of the model.

RESULTS

Surface Sample Assemblages

The living and dead assemblages in the 31 surface samples from Mokomoko Inlet are plotted in Figure 2, while Figure 3 provides scanning electron micrographs of all species encountered. Table A1 provides full assemblage data.

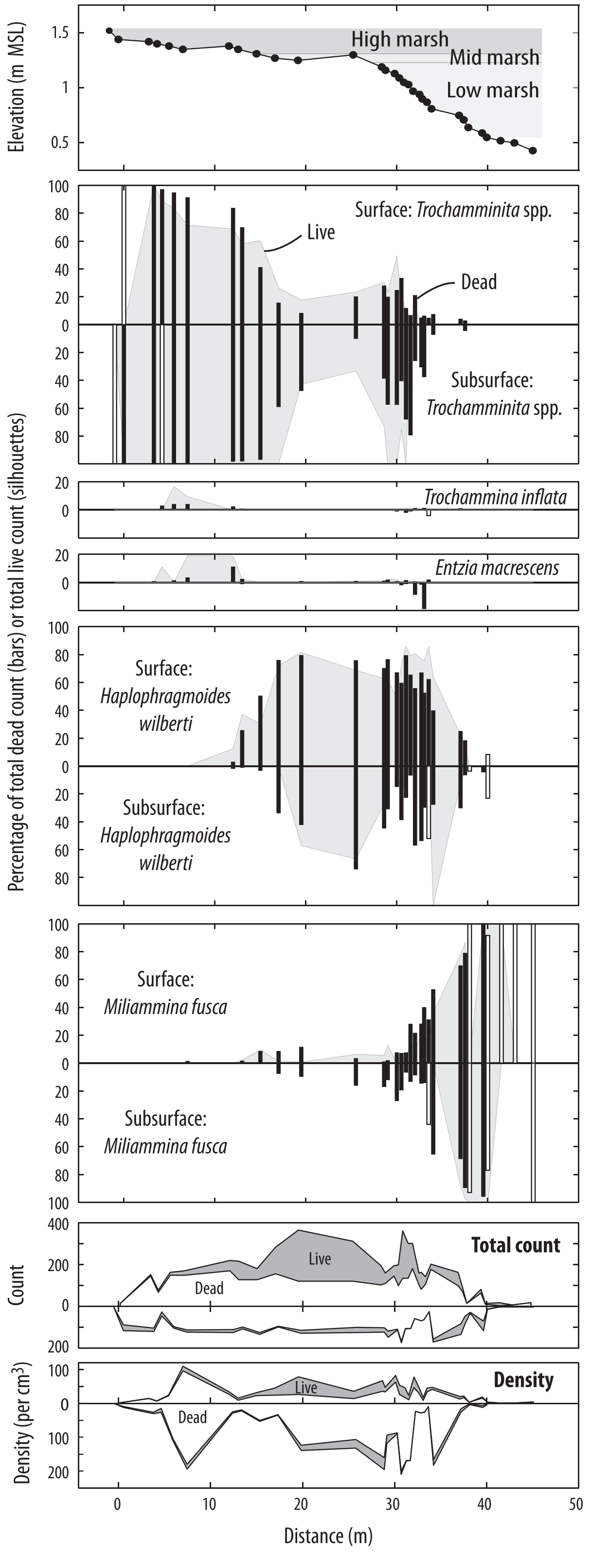

FIGURE 2. Lateral distribution of foraminifera in the Mokomoko Inlet surface (0–1 cm) and subsurface (3–4 cm) samples. Dead assemblages are displayed as bars (filled for samples with total dead counts >30, outlined for dead counts <30), live assemblages as silhouettes. The subsurface graphs are inverted to facilitate comparison between the subsurface and co-located surface samples. Low, mid, and high marsh zones correspond to vegetation zones 1, 2, and 3 of Garrett et al. (2022).

The surface samples contain six species of foraminifera, including the two species that are grouped here as *Trochamminita* spp. to allow comparison with datasets that do not make this distinction. The highest elevation sample (1.52 m MSL) contains no foraminifera and all species encountered in the other samples have agglutinated tests. Dead test concentrations average 34 per cm^3 (range: 0–109 per cm^3), with seven samples, mainly from the lowest elevations, having densities below 10 per cm^3. Of the 31 samples, 24 have dead counts of 30 or more. The high marsh is dominated by *Trochamminita* spp., which reaches up to 100% of the dead assemblage at the highest elevations. *Entzia macrescens* and *Trochammina inflata* are also encountered in high marsh samples; the latter is the only species which does not exceed 5% of the total dead assemblage in any surface sample. *Haplophragmoides wilberti* is the dominant mid marsh species, constituting 50–80% of the dead assemblage. In the low marsh and mudflat, *Miliammina fusca* dominates, reaching 100% of the dead assemblage at the lowest elevations.

Rose Bengal-stained foraminifera, which we assumed to be living at the time of sample collection, are found in 26 of the 31 surface samples (Fig. 2), with total live specimen counts averaging 63 (range: 0–244 specimens). For samples with dead counts >30, live specimens constitute 34% of the total count on average (range: 0 to 67%) and live test concentrations across all samples average 23 per cm^3 (range: 0–156 per cm^3). Thirteen samples have live densities below 10 per cm^3. All species found in the dead assemblage are represented in the living assemblage, with no additional species encountered. The distribution of live foraminifera closely corresponds to the dead assemblage distribution (Fig. 2).

SUBSURFACE SAMPLE ASSEMBLAGES

The 31 subsurface samples contain eight species of foraminifera, of which four exceed 5% of the total dead count in at least one sample (Fig. 2, Table A2). The species not encountered in the surface samples — *Ammobaculites exiguus*, *Portatrochammina sorosa*, and *Cribroelphidium excavatum* — are each represented by a single specimen. Dead assemblage counts average 89 (range: 0–174) and concentrations average 60 per cm^3 (range: 0–200 per cm^3). Twenty-three samples have dead counts of 30 or more and two samples from the seaward end of the transect are devoid of foraminifera. The subsurface samples broadly display the same distribution of dead assemblages as the surface samples, with *Trochamminita* spp. at the landward end of the transect and *H. wilberti* and *M. fusca* at progressively lower elevations (Fig. 2). The zone of *Trochamminita* spp. dominance in the high marsh extends further down the transect in the subsurface samples, with abundances exceeding 80% between 0 m and 15 m along the transect, compared with 0 m to 12 m in the surface samples. *Trochamminita* spp. are also dominant (40 to 80%) between 29 m and 32 m along the transect in the subsurface samples. By contrast, *H. wilberti* is less abundant in this interval. While *E. macrescens* is present in most high marsh surface samples and reaches a maximum towards the top of the transect, its maximum subsurface abundance (19% of the dead count) is in the low marsh, with few specimens encountered at higher elevations. As in the surface samples, *M. fusca* is dominant in the subsurface

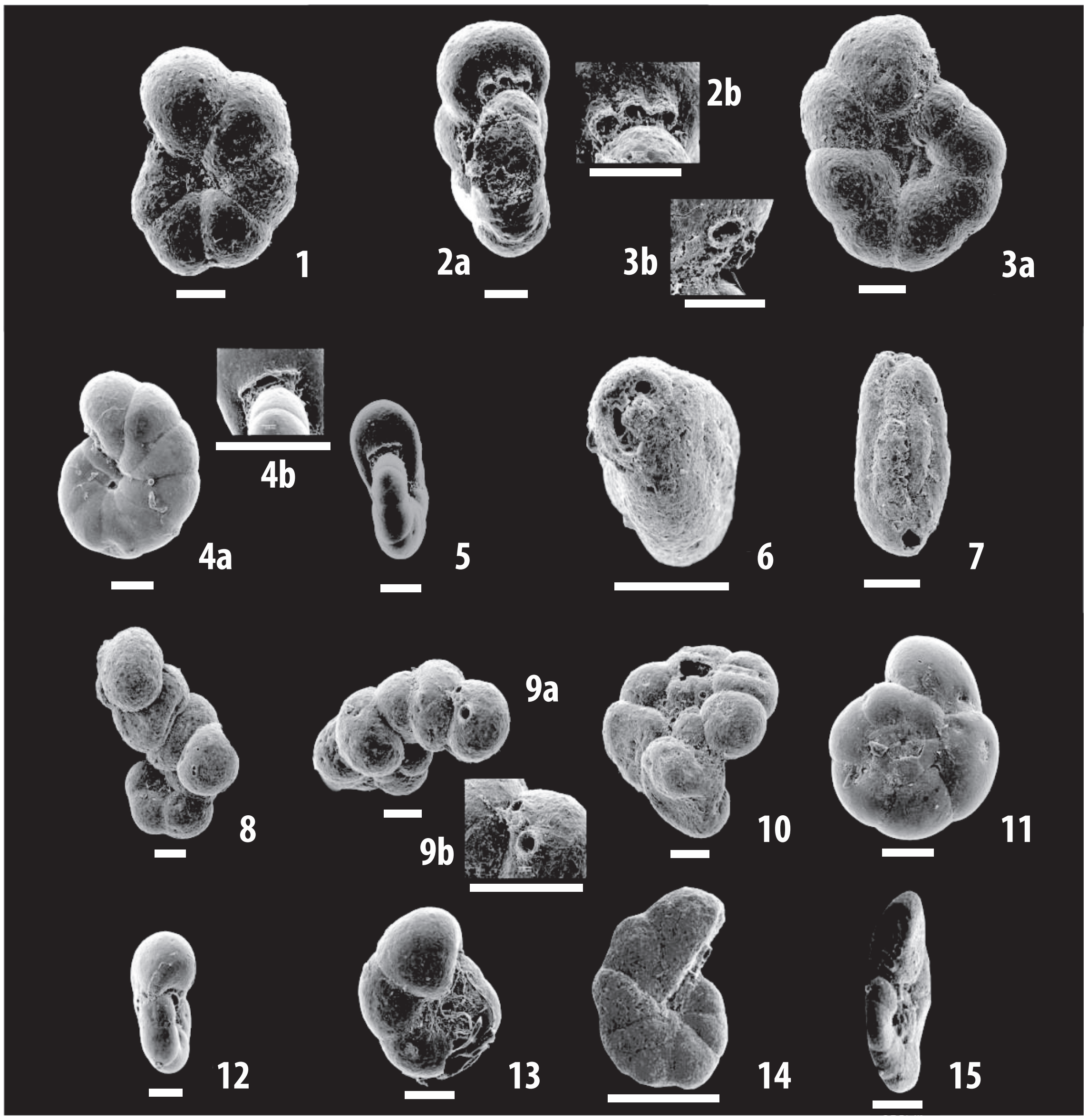

FIGURE 3. Scanning electron micrographs of the species encountered in the surface and subsurface samples from Mokomoko Inlet, southern New Zealand. All scale bars are 100 μm in length. **1–3** *Trochamminita salsa* (Cushman & Brönniman, 1948), including aperture views. **4–5** *Haplophragmoides wilberti* (Anderson, 1953), including aperture view. **6–7** *Milliamina fusca* (Brady, 1870). **8–10** *Trochamminita irregularis* (Cushman & Brönniman, 1948) including aperture view. **11–13** *Trochammina inflata* (Montagu, 1808). **14–15** *Entzia macrescens* (Brady 1870). We group *T. salsa* and *T. irregularis* as *Trochamminita* spp. to allow comparison with datasets that do not make this distinction.

samples from the low marsh. However, the limit of abundances >5% is further landward in the surface (17 m) compared to the subsurface (15 m).

Stained specimens are encountered in 22 of the 31 subsurface samples, with counts averaging 12 (range: 0–50 specimens). Living specimens contribute 11% of the total subsurface count on average (range: 0–45%). Live concentrations average 2 per cm^3, with only 7 of the 31 samples having concentrations greater than 10 per cm^3. The three species that make up the live subsurface assemblage are the three that are most abundant in the surface and subsurface dead assemblages: *Trochamminita* spp., *H. wilberti*, and *M. fusca* (Fig. 2). No additional species are found living infaunally that are not represented in the surface samples. While live specimens of *M. fusca* are present in all samples between 13 and 45 m in the surface transect, the species is restricted to between 37 and 45 m in the subsurface living assemblage. Live *H. wilberti* specimens are similarly found further landward in the surface than the subsurface samples. Living *E. macrescens* and *T. inflata* specimens are absent from the subsurface assemblage, despite contributing up to 15 to 20% of the living assemblage in the surface samples.

SEDIMENT COMPACTION

Table 1 and Figure 4 display the physical and geotechnical properties of the modern surface samples from Mokomoko

TABLE 1. Physical and geotechnical properties of the nine modern surface samples from the salt marsh at Mokomoko Inlet. The recompression index, C_r, describes the compressibility of the sample in its pre-yield, reduced compressibility condition. The compression index, C_c, describes the compressibility of the sample in its post-yield, increased-compressibility condition. The yield stress, σ'y, defines the transition from reduced to increased compressibility states.

Sample number	Distance along transect (m)	Marsh vegetation zone	Loss on ignition (%)	Particle density, G_s	Voids ratio at 1 kPa, e_1	Recompression index, C_r	Compression index, C_c	Yield stress, σ'_y (kPa)
MKT-GT01	3.3	High	61.5	1.67	10.80	0.080	4.915	7.05
MKT-GT02	7.0	High	57.2	1.83	10.12	0.102	3.860	4.47
MKT-GT03	12.0	High	49.3	2.05	13.11	0.092	4.909	4.72
MKT-GT04	17.0	Mid	37.9	2.07	7.79	0.041	3.540	9.57
MKT-GT05	22.0	Mid	26.5	2.20	5.02	0.029	1.013	10.20
MKT-GT06	25.5	Mid	16.3	2.28	3.87	0.040	1.482	8.43
MKT-GT07	30.0	Low	16.2	2.35	4.89	0.057	2.369	16.0
MKT-GT08	36.0	Low	3.23	2.63	1.43	0.012	0.180	4.00
MKT-GT09	43.0	Low	0.86	2.77	0.74	6.908×10^{-5}	0.030	2.00

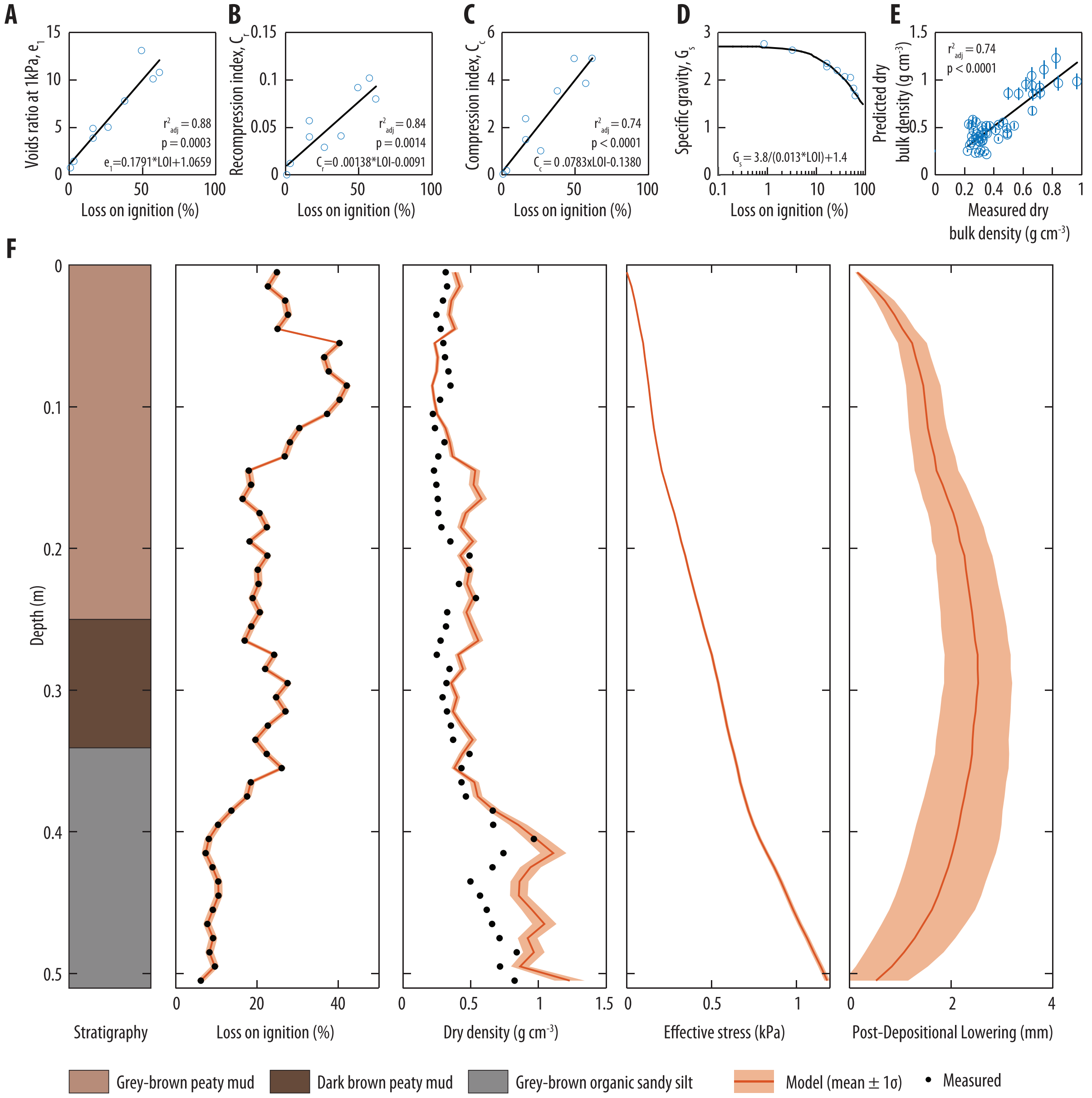

FIGURE 4. Estimation of post-depositional lowering (PDL) in core MKT-18.5 using a geotechnical model. (A–D) Relationships between organic content (measured by loss on ignition, LOI) and geotechnical properties of modern salt-marsh sediment at Mokomoko Inlet. In (D), the model equation is from Hobbs (1986). (E) Comparison of measured and predicted dry density. (F) Downcore stratigraphy, physical and geotechnical properties of, and estimated post-depositional lowering (PDL) in, core MKT-18.5.

Inlet. The LOI ranged from 1% in the low marsh vegetation zone to 62% in the high marsh. In surface samples tested for compression behaviour, we observed statistically significant positive relationships between LOI and e_1, C_r, and C_c (Figs. 4A–C), which is consistent with previous studies (Brain et al., 2012, 2017; Kemp et al., 2018).

Figure 4F displays the stratigraphy of core MKT-18.5, as previously presented by Garrett et al. (2022). The core consists of 0.17 m of organic sandy silt (LOI ≈ 6–25%) overlain by 0.34 m of peaty mud, in which LOI increases from ~22% between 0.34 m and 0.15 m depth to ~25–40% between 0.15 m and the modern ground surface. As such, the range of LOI values observed in our modern geotechnical samples is representative of those observed in the core.

Modelled dry density values correlate well ($r^2_{\text{adj}} = 0.74$; $p < 0.0001$) with those measured throughout the core (Fig. 4E), and the model reproduces downcore trends in dry density (Fig. 4F). Modelled effective stress increases to 1.18 kPa at 0.51 m depth (Fig. 4F); this value is less than all observed and modelled values of compressive yield stress. As such, the sediment is in a low-compressibility condition throughout the core. Maximum PDL (2.5 mm ± 0.7 mm) is experienced at 0.29 m depth in the core (Fig. 4F).

DISCUSSION

Assemblage Changes Between the Subsurface and Surface

Paired surface and subsurface samples from Mokomoko Inlet are predominantly similar (Fig. 2). Of the 22 sample pairs with dead counts greater than 30 in both the surface and the subsurface, only four have similarity coefficients less than the 50th percentile of the similarity coefficients amongst all the surface samples (Fig. 5). The most similar pairs are at the upper and lower ends of the transect, where near-monotypic assemblages of *Trochamminita* spp. or *Miliammina fusca* characterise both the surface and subsurface. Greater differences between the surface and subsurface are seen in the mid marsh, where assemblages are more diverse around the transitions between faunal zones.

Five main processes lead to differences between dead foraminiferal assemblages in subsurface and surface samples: changes in environmental conditions, addition of tests through infaunality, differential loss due to taphonomic processes, redistribution of tests following erosion or through bioturbation, and stochastic variability (Berkeley et al., 2007; Hayward et al., 2014). While the surface and subsurface assemblages from Mokomoko Inlet are largely similar, there are several key differences that may be explained by these processes. In the following sections, we focus on recent sea-level change, infaunality, and taphonomy. While sediment erosion and deposition has been identified as important at other sites in southern New Zealand (Grenfell et al., 2012; Figueira & Hayward, 2014), the Mokomoko Inlet site lacks evidence of these processes such as a marsh-front cliff. Bioturbation may cause vertical redistribution of sediment and foraminiferal tests (e.g., Debenay et al., 2004), but this is considered insignificant at Mokomoko Inlet due to lack of visible evidence for burrowing by crabs or other animals.

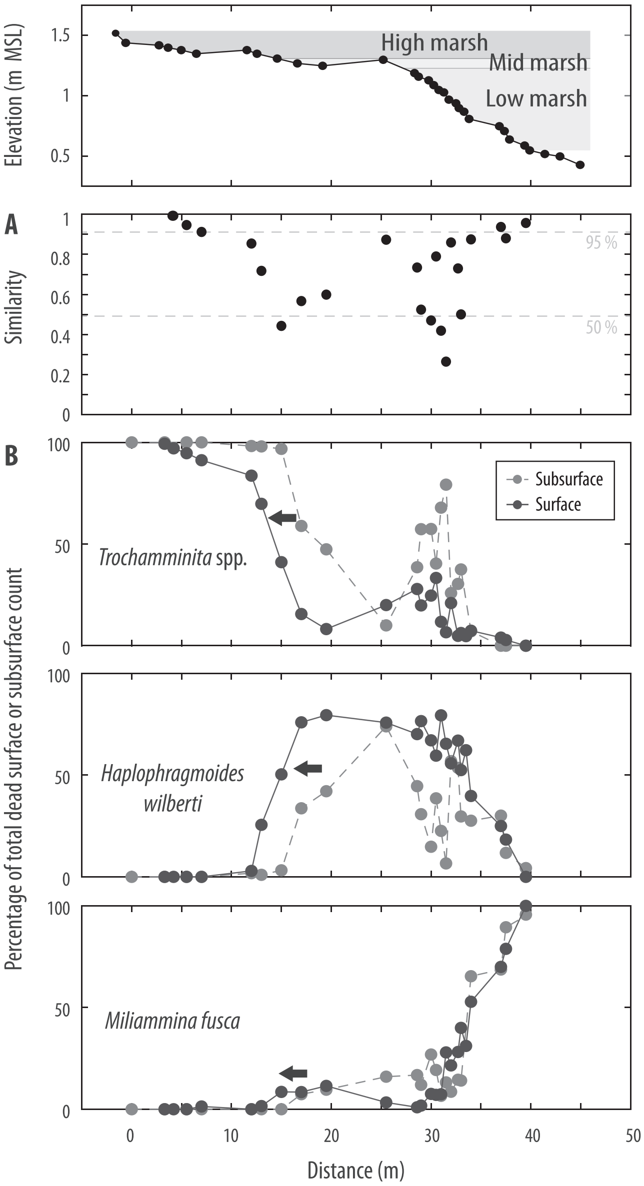

Figure 5. (A) Distribution of similarity coefficients (chord distance) in paired surface and subsurface samples. We calculate coefficients for all sample pairs with total dead counts >30 in both the surface and subsurface (n = 22). Dashed horizontal lines mark the 50th and 95th percentile of the coefficients between all of the modern samples. (B) Lateral shifts in the distribution of key species between the subsurface and surface samples, illustrated through comparison of their percentage contribution to the total dead count. We exclude all samples with dead counts <30. Black arrows highlight areas where the lateral shifts are most apparent.

Environmental Change

The zones of *Trochamminita* spp., *H. wilberti*, and *M. fusca* dominance are each located further inland in the dead assemblage of the surface samples than in the subsurface (Fig. 5). The landward shift in the zonation is consistent with a transgression, as would be expected if recent sea-level rise exceeded the rate of sediment accumulation. Such a transgression is also implied by the increase in *H. wilberti* and decrease in *T. salsa* in the uppermost centimetre of core

MKT-18.5 (Garrett et al., 2022, their figure 6). The RSL reconstruction of Garrett et al. (2022), using a Gaussian process model, indicates relatively slow rates of sea-level rise over the time period relating to the uppermost 4 cm of sedimentation: ~1.5 mm a^{-1} between 1975–1994 CE (2σ range) and 2006. Nevertheless, when taken in isolation from the underlying layers, the uppermost 4 cm imply greater rates of RSL rise that are not reflected by the Gaussian process model (Fig. A2). While the vertical and temporal uncertainties are large compared to the length of the interval of interest, the midpoint estimate is ~6 mm a^{-1} (Garrett et al., 2022, their figure 7b; Fig. A2). The identification of evidence for a transgression from the comparison of subsurface and surface assemblages questions the low rates modelled at the end of the MKT-18.5 record and suggests a more rapid RSL rise at Mokomoko in the late 20th century than previously stated. The Bluff tide gauge, located approximately 8 km southeast of Mokomoko Inlet (Fig. 1), lacks data from 1962–1984 and 1991–1998, but monthly data indicate a rise >2 mm a^{-1} between 1984 and 2006 and potentially more over shorter time periods (PSMSL, 2022). Aside from sea-level rise, we cannot discount the possibility of other environmental changes resulting in transitions in foraminiferal assemblages. Land-use changes within the catchment, changing nutrient inputs, or pollution events could also result in unquantified differences between subsurface and surface assemblages.

Infaunality

Overprinting spatial shifts due to sea-level rise, infaunality may alter assemblage compositions after sediment deposition. Previous analyses of down-core trends in the concentration of live foraminifera have revealed the occurrence of infaunal test production at depths, in some cases, exceeding several decimetres (e.g., Goldstein & Harben, 1993; Goldstein et al., 1995; Hippensteel et al., 2000; Horton & Edwards, 2006; Hayward et al., 2014; Milker et al., 2015; Chen et al., 2020). While our sample set does not allow us to identify the full depth distribution of infaunality at Mokomoko Inlet, the subsurface samples do allow for an analysis of the importance of infaunality at a specific depth interval across the marsh. In the 23 subsurface samples with dead counts >30, live specimens contribute an average of 13% (range 0–45%) to the total count. The highest proportions of living specimens are in the low concentration *M. fusca*-dominated samples from the low marsh (Fig. 2); however, these proportions may stem from taphonomic loss of dead specimens (section 5.1.3). The presence of stained *M. fusca* specimens in the subsurface samples nevertheless accords with the known preference of this species for epifaunal or shallow infaunal depths (Goldstein et al., 1995; Ozarko et al., 1997; Goldstein & Watkins, 1999). *Trochamminita* spp.-dominated samples from the high marsh, which are of greater relevance for RSL reconstructions, have lower living percentages, averaging 10% (range: 6–23%).

The live infaunal distributions of the three dominant species, *Trochamminita* spp., *H. wilberti*, and *M. fusca*, closely correspond to their respective dead surface and subsurface distributions (Fig. 2), and no additional species are encountered living infaunally. Consequently, we do not anticipate that infaunality dramatically influences assemblage composition at 3–4 cm depth. Nevertheless, we observe that *H. wilberti* is less common and *Trochamminita* spp. more common in the dead assemblage in most of the subsurface samples than at the surface (Fig. 6). *Trochamminita* spp. are also found at greater percentages of the total live count in the subsurface; greater infaunal production may therefore contribute to the difference between the dead surface and subsurface abundances of these species. *Trochamminita* spp. are reported as living epifaunally or in the shallow subsurface at other locations (Ozarko et al., 1997; Figueira et al., 2012). Hypothesised lower subsurface production of *H. wilberti* tests contrasts with previous studies that report the species as preferentially infaunal (Goldstein & Harben, 1993; Ozarko et al., 1997; Hippensteel et al., 2000; Duchemin et al., 2005; Chen et al., 2020), but may agree with results from other New Zealand marshes that identify *T. salsa* as living at greater depths than *H. wilberti* (Hayward et al., 2014).

Taphonomy

Differential rates of degradation and loss of tests provide an additional mechanism that may contribute to differences between surface and subsurface assemblages. Potential taphonomic processes include mechanical breakage and abrasion, bioerosion, oxidation of organic cements, and dissolution (Goldstein & Watkins, 1999; Berkeley et al., 2007). The similarity between the relative abundances of species in the surface and subsurface dead assemblages indicates that taphonomic processes do not cause substantial modifications to assemblages in shallow subsurface samples from Mokomoko Inlet. Of the 31 sample pairs, higher test densities are found in the subsurface rather than the surface in 18 instances (Fig. 2). Test densities are, nevertheless, consistently lower in the subsurface in the *M. fusca*-dominated samples between 37 and 45 m along the transect. This may point towards the loss of this species, perhaps due to mechanical breakage and test fracturing associated with more frequent inundation and greater sediment mobility in the low marsh and upper mudflat. Such losses of *M. fusca* have also been reported from the eastern USA, where the degradation of organic cements has also been suggested (Culver et al., 1996; Goldstein & Watkins, 1999; Culver & Horton, 2005; Chen et al., 2020).

The reduced subsurface percentages of *H. wilberti* (Fig. 6, section 5.1.2) are unlikely to reflect taphonomy as the species is regarded as relatively resistant to degradation (Goldstein et al., 1995; Goldstein & Watkins, 1999). Little test disaggregation has been observed in the uppermost 30 cm of New Zealand marshes (Hayward et al., 2014).

Although only found in low numbers, *E. macrescens* and *T. inflata* are more common in the surface samples, both as stained and unstained tests (Fig. 6). Amongst the 3018 unstained foraminifera enumerated in the surface samples, 41 (1.4%) were *E. macrescens*; in the subsurface samples 23 of 2395 specimens (0.9%) were of this species. Taphonomic loss of the thin-walled *E. macrescens* may explain the lower subsurface abundance of this species and the species' rarity in fossil assemblages from late Holocene cores (e.g., Gehrels et al., 2008; Figueira, 2012; Garrett et al., 2022). Selective degradation or loss of *E. macrescens* has also been

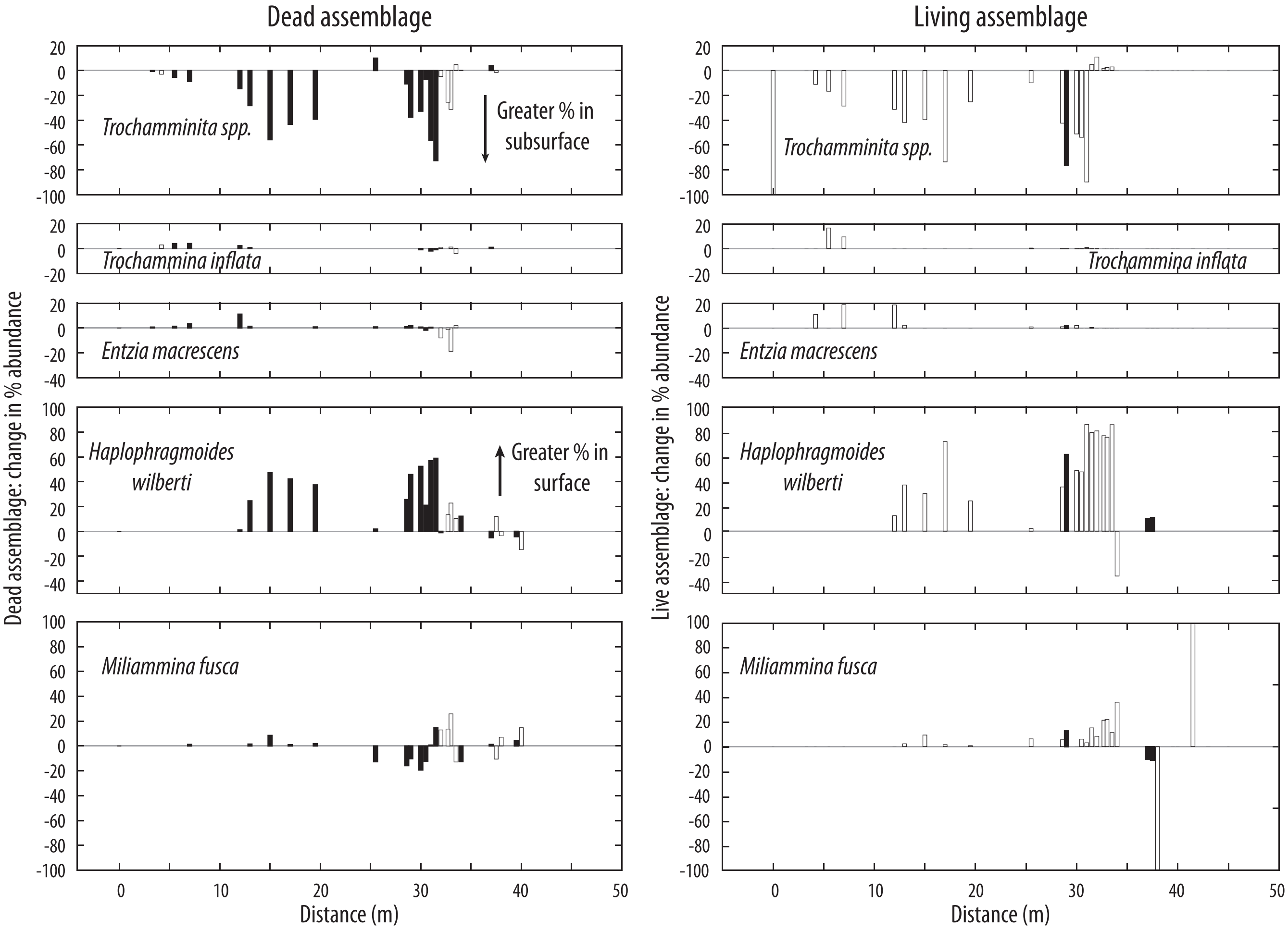

FIGURE 6. Change in the percentage abundance of foraminiferal species between the Mokomoko Inlet surface and subsurface samples. Positive values indicate greater percentages in the surface samples. Bars are filled where total dead (left) or total live (right) counts in both the paired surface and subsurface samples are >30.

recognised in North American marshes (e.g., Patterson, 1990). In contrast to other tidal marshes in New Zealand (Hayward et al., 1999; Southall et al., 2006; Grenfell et al., 2012), *T. inflata* is unusually rare at Mokomoko Inlet. We encountered 23 unstained *T. inflata* specimens in the surface samples (0.8% of the surface total), compared to five specimens in the subsurface samples (0.2%). The low abundances of this species may reflect the hypohaline rather than euhaline nature of the site (Hayward et al., 2014; Garrett et al., 2022). As these large, robust tests are unlikely to be preferentially lost by post-mortem disintegration, we may conclude that relative scarcity in subsurface samples and lower abundances in surface samples are unlikely to reflect taphonomic processes, but rather may indicate the recent establishment of a small patch of this species at the site.

IMPLICATIONS FOR SEA-LEVEL RECONSTRUCTIONS

Reconstructing Palaeomarsh Surface Elevations

To test whether infaunality and taphonomy result in changes to marsh surface elevation reconstructions, we calibrate the subsurface assemblages using the local and regional transfer functions developed by Garrett et al. (2022). For the majority of the subsurface samples with sufficient dead counts, model predictions are very close to the field elevations (Fig. 7), indicating that infaunality and early-stage taphonomic changes have not resulted in significant departures from the observed elevations. The local model predictions are on average 0.07 m higher than the field elevations, with 2σ uncertainties of ±0.16 m. The regional model predictions are 0.08 m above the field elevations on average, with 2σ uncertainties of ±0.14 m. Excluding the five samples discussed in the following paragraph reduces the residuals for the local and regional models to 0.02 m and 0.03 m, respectively. As the field elevations are expressed relative to contemporary MSL, the residuals between the predicted and observed subsurface elevations partly reflect the increase in the elevation of this datum over time resulting from sea-level rise.

Several samples from lower elevations demonstrate poor agreement between model predictions and field observations. Five predictions between 31 and 33 m along the transect plot 0.2 to 0.3 m above their observed field elevations

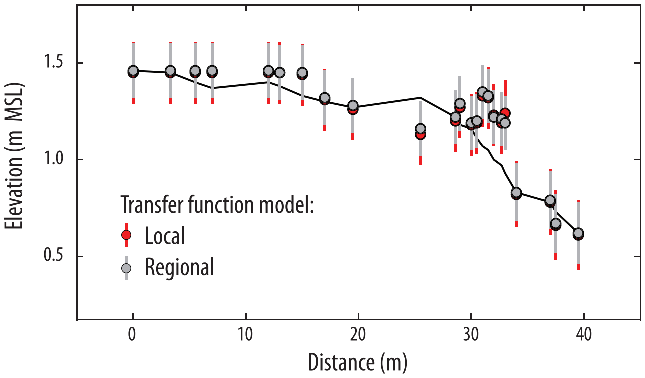

FIGURE 7. Local and regional transfer function model predictions for the Mokomoko Inlet subsurface samples derived using the transfer functions developed by Garrett et al. (2022) and applied using the C2 software (Juggins, 2007). The black line shows actual sample elevations.

(Fig. 7). These samples contain lower abundances of *M. fusca* and *H. wilberti* and greater abundances of *Trochamminita* spp. than the co-located surface samples. Such faunal trends are consistent with the combined effects of infaunal production of *Trochamminita* spp. tests, taphonomic loss of *M. fusca*, and the recent establishment of *H. wilberti*.

Our subsurface reconstruction experiment reinforces the generally established approach of selecting high marsh sediments for foraminifera-based RSL reconstructions (Gehrels, 2000; Chen et al., 2020). High marsh samples from Mokomoko Inlet provide precise and accurate reconstructions, whereas the use of low marsh sediments may result in reconstructions of erroneously high marsh-surface elevations. Care must particularly be taken when reconstructing sea-level change from transgressive sequences; a reconstruction based on a single core featuring low marsh sediments overlying high marsh sediments could underpredict the real magnitude of sea-level rise.

Reconstructing RSL at Mokomoko Inlet

The Mokomoko Inlet RSL reconstruction (Garrett et al., 2022) was based on the upper, organic part of the core only; the underlying sandy silt was excluded due to the co-occurrence of *Trochamminita* spp. (specifically *T. salsa*) and *M. fusca*, an assemblage that lacked a modern analogue. This assemblage may, however, be explained by the infaunal occurrence of *T. salsa* and reductions in the density of *M. fusca* due to post-mortem loss of tests. The presence of *M. fusca* is consistent with the inorganic sedimentation, while *T. salsa* may constitute a subsequent infaunal addition following the development of the overlying organic salt-marsh deposit. While the ability of *T. salsa* to infaunally inhabit inorganic sediments remains somewhat speculative, low sedimentation rates during the early development of the salt marsh will have increased the time during which the silty sand was within the infaunal zone. Subsequent more rapid sedimentation, resulting from increased accommodation space and enhanced by trapping of sediment by vegetation, and the consistency of the stratigraphy likely reduces the potential for infaunality to result in assemblage modification in the sediments employed for the RSL reconstruction.

The distinct stratigraphies of Southern Hemisphere salt marshes — the result of sea-level histories that include, in many regions, a mid-Holocene sea-level highstand (Compton, 2001; Woodroffe, 2009) — require that infaunality is considered when reconstructing sea-level changes from salt-marsh sediments. Salt-marsh deposits are much thinner than in the well-studied North Atlantic salt marshes of the eastern USA and eastern Canada (Gehrels, 2000; Kemp et al., 2018), because they could only accumulate once the falling sea level from the mid Holocene highstand had levelled off or reversed (Hayward et al., 2015b). The vertical accommodation space in which the marshes developed is very small compared to their North Atlantic counterparts where sea level has been rising throughout the Holocene. This increases the potential for infaunal processes in Southern Hemisphere salt marshes to modify foraminiferal assemblages found within much older sediments.

Modern Sample Thickness

Modern foraminiferal training sets for RSL reconstructions are widely based on samples from the uppermost 1 cm (Scott & Medioli, 1978; Horton & Edwards, 2003). Nevertheless, suggestions have been made to use thicker samples to better reflect infaunal production (e.g., Patterson et al., 1999). We identify differences between 0–1 cm and 3–4 cm that are related to environmental change and transgression (i.e., a distinct landward shift of foraminiferal zones in response to rising sea level; section 5.1.1). In locations where transgressions are underway, which may include many sites on temperate coastlines, thicker samples should therefore not be used. While 0–1-cm samples may miss infaunal contributions, thicker samples contain sediments with different relationships to tidal levels and preclude high-resolution reconstructions from the uppermost centimetres of salt-marsh sediment.

SEDIMENT COMPACTION

Our application of a geotechnical model to quantify the effects of sediment compaction on relative sea-level reconstructions from core MKT-18.5 demonstrates that PDL (maximum of 2.5 ± 0.7 mm at 29 cm depth) is negligible relative to the rates of reconstructed sea-level change for the early- to mid-20th Century. This finding supports previous work (e.g., Gehrels et al., 2008; Brain et al., 2012; Garrett et al., 2022) and confirms the contention of Garrett et al. (2022) that the rapid rates of sea-level rise reconstructed for the early- to mid-20th century are not an artefact of sediment compaction.

CONCLUSIONS

Salt-marsh foraminifera at Mokomoko Inlet, southern New Zealand, display elevation-controlled zonation in their surficial assemblages. The highest elevations are dominated by *Trochamminita* spp., while lower elevations are progressively dominated by *H. wilberti* and *M. fusca*. A novel sample set, with each surface sample co-located with a subsurface sample from 3–4 cm depth, allows us to assess the spatial distribution of infaunality and early-stage taphonomic changes. The surface and subsurface assemblages are similar, but we observe a landward and upward shift in the zonation that is consistent with recent sea-level rise at a rate greater than the rise in the elevation of the marsh surface. This transgression suggests the previously reconstructed rate of recent sea-level rise may have been underestimated. Infaunality does not result in significant changes to assemblages, with live infaunal distributions closely corresponding to the dead surface assemblages. Taphonomic loss within the uppermost few centimetres may largely be limited to fine-walled species such as *E. macrescens*, which is relatively rare in this region, and *M. fusca*. Transfer function-based reconstructions of the depositional elevation of the subsurface samples are largely insensitive to these changes; however, sea-level reconstructions should focus on high marsh environments where observations and model predictions most closely align. Application of a geotechnical model confirms that sediment compaction is negligible, resulting in only millimetre-scale post-depositional lowering. We conclude that infaunality, taphonomy, and sediment compaction do not significantly alter foraminifera-based sea-level reconstructions derived from salt-marsh sediments in southern New Zealand. David Scott's discovery in 1978 that salt-marsh foraminifera are highly accurate and precise indicators of past sea levels remains valid today and continues to underpin research along coastlines around the world.

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