Distribution of modern salt-marsh foraminifera from Churchhaven Marsh, South Africa: Implications for high-resolution sea-level reconstructions in the Southern Hemisphere

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Background and rationale

Benthic foraminifera from salt marshes have been successfully utilised as sea-level indicators, particularly in the Northern Hemisphere (Gehrels et al., 2006; Barnett et al., 2015; Kemp et al., 2017; 2018; 2024; Stearns et al., 2023), where they have been used to extend sea-level observations prior to the instrumental era (~1800 CE – present). Assessing relative sea-level changes back through the instrumental era and into the Common Era (0 CE – present) is crucial to understand the drivers, rates and magnitudes of sea-level change under 'natural' forcing, which aids in generating future projections of sea-level rise. Whilst we now have a relatively thorough understanding of sea-level change over the Common Era in the North Atlantic (Walker et al., 2021), comparatively little is known about past sea-level change in the Southern Hemisphere. Recent work has sought to increase the number of "high-resolution" sea-level reconstructions from the Western Pacific (Gehrels et al., 2008; Gehrels et al., 2012; Garrett et al., 2022; Williams et al., 2023; King et al., 2024) and South Atlantic (Frederikse et al., 2021) to understand the drivers of recent, historical sea-level rise, though numbers remain low – roughly 68 % of Common Era reconstructions derive from the Northern Hemisphere (**Fig. 1**) and the majority of "high-resolution" reconstructions are derived from the North Atlantic. As such, our understanding of historical regional variability in sea level, and our estimates of Common Era global mean sea level, are biased. This becomes problematic when trying to ascertain, for example, regional sea-level budgets (Dangendorf et al., 2024).

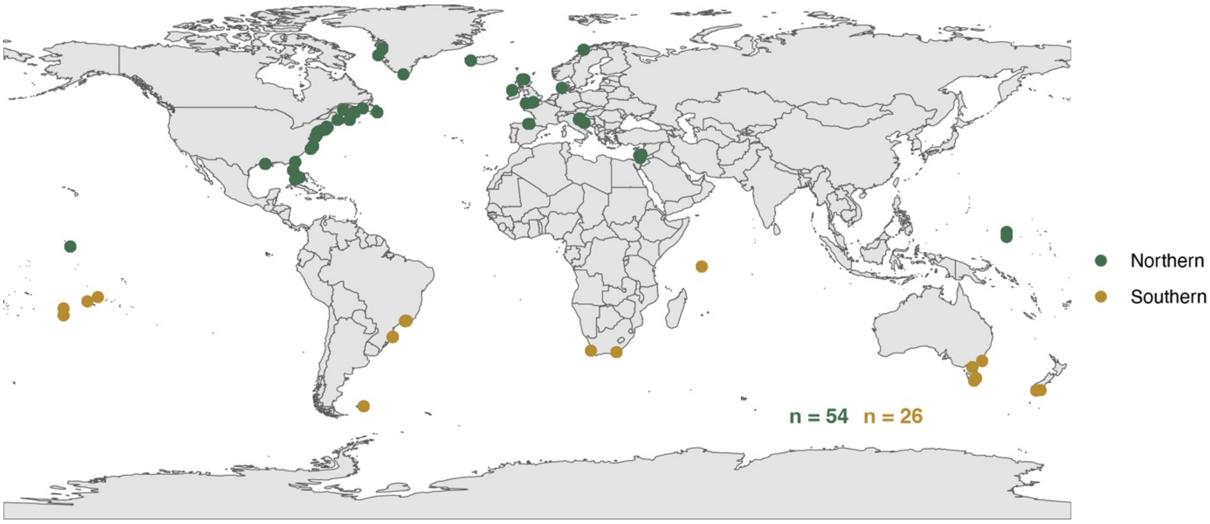

Figure 1: Distribution of Common Era sea-level reconstructions (0 CE–present).

High-resolution sea-level reconstructions (defined here as reconstructions which allow for investigations of decadal sea-level variability) have typically been generated from high salt-marsh environments, though recent work (Majewski et al., 2022), has also utilised microatolls to reconstruct sea level over the 19th and 20th century. Salt marshes accrete in response to sea-level rise and, dependent upon their sedimentation rate and the availability of dateable material, can yield sea-level reconstructions with multi-annual – sub-decadal resolution. Whilst sediment has routinely been utilised for Late Quaternary and Holocene sea-level reconstructions, most high-resolution reconstructions employ the use of modern and fossil microfossils, typically foraminifera, diatoms, testate amoebae and occasionally pollen in a transfer function approach (*e.g.* Woodroffe, 2005; Engelhart et al., 2007; Kemp et al., 2009; Barlow et al., 2013; Watcham et al., 2013; Strachan et al., 2015; Barnett et al., 2017; Williams et al., 2021), to produce palaeo sea-level estimates with decimetre-scale resolution. Both flora and fauna are zoned in salt marshes relative to the tide, influenced by the frequency and duration of tidal inundation. By quantifying the relationship between modern foraminifera and their elevation, using reasoning by analogy, we can ascertain the palaeomarsh surface when quantifying fossil assemblages (**Fig. 2**).

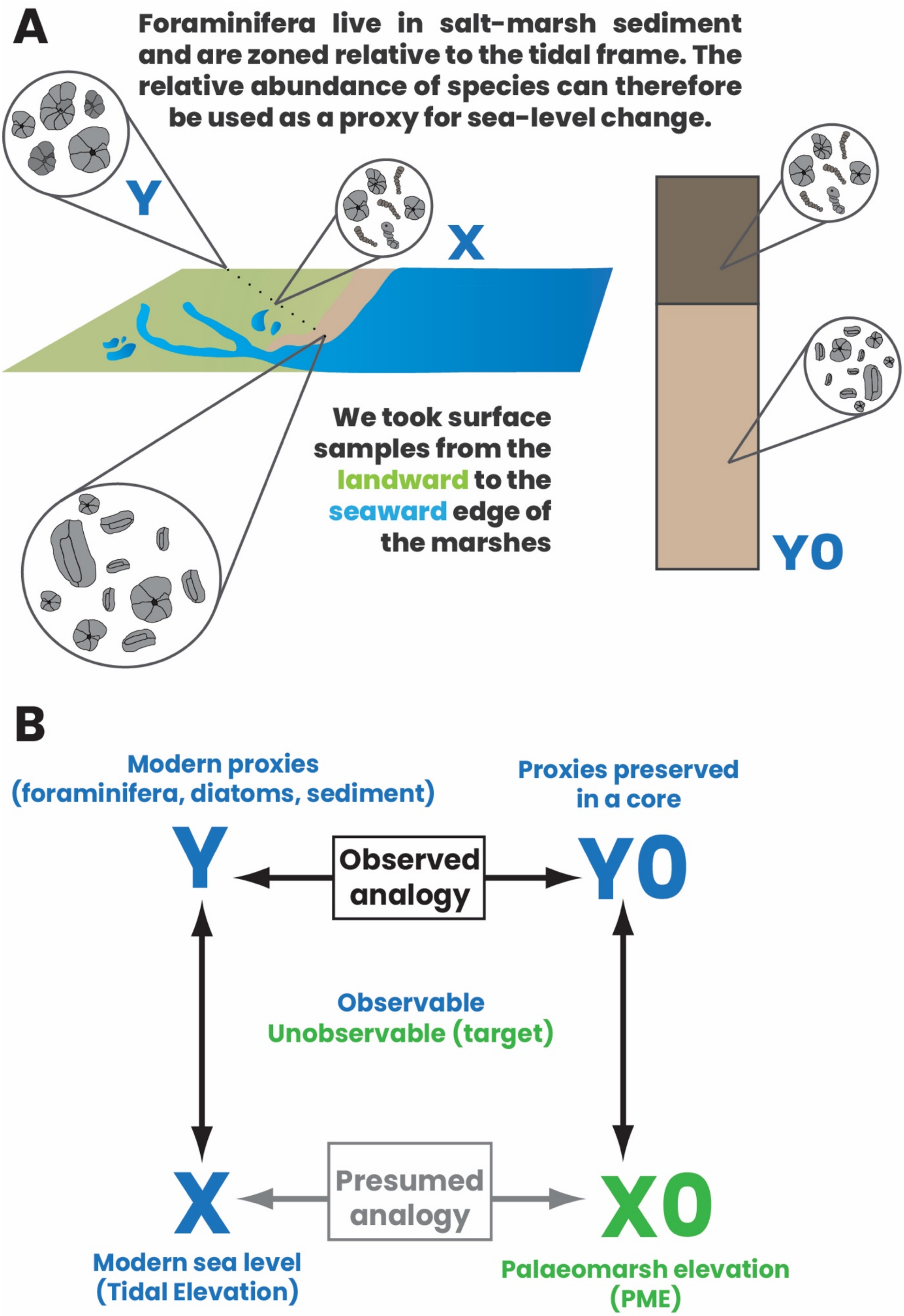
A
Foraminifera live in salt-marsh sediment and are zoned relative to the tidal frame. The relative abundance of species can therefore be used as a proxy for sea-level change.
Y
X
YO
We took surface samples from the landward to the seaward edge of the marshes
B
Modern proxies (foraminifera, diatoms, sediment)
Proxies preserved in a core
Y
Observed analogy
YO
Observable
Unobservable (target)
X
Presumed analogy
XO
Modern sea level (Tidal Elevation)
Palaeomarsh elevation (PME)

Figure 2. A. Schematic of a salt-marsh environment and examples of common benthic foraminifera found in high, mid and low salt-marsh environments in South Africa. Salt marsh schematic has been adapted from the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science. **B.** Reasoning by analogy approach used to reconstruct past sea level using microfossils (adapted by Andrew Kemp *c.f.* (Jackson and Williams, 2004)).

The southern and western coastlines of South Africa are located in a temperate zone favourable for salt-marsh growth, are virtually free of vertical land movements, are largely tectonically stable, and have a microtidal regime (therefore vertical error on reconstructions is lower (Williams et al., 2021)). Tide gauges in the region are temporally limited (~1950s-present), and there is yet to be a full appraisal of the driving forces of historical (*i.e.* 19th and 20th century) sea-level change in the region, comparing proxy-derived reconstructions to historical sea-level budgets (as has been done for other Southern Hemisphere sites (*e.g.* Frederikse et al., 2021; Garrett et al., 2022; Williams et al., 2023)). As such, this project sought to generate a new high-resolution reconstruction from Churchhaven salt marsh, Langebaan, South Africa (-33.198, 18.128) to supplement temporally, and spatially-limited tide-gauge records, assess recent trends of sea-level change, quantify driving processes, and add to a global database of proxy records to better understand Common Era sea-level change. The first step in this process was to assess the distribution of modern foraminifera and their relationship to the tidal frame at Churchhaven (*i.e.* Y and X **Fig. 2**). Results presented here are preliminary, with further samples to enumerate. As such, final transfer functions are not presented. Rather, this article focuses on the identification of contemporary benthic foraminifera, and distribution of them, at the site. The fieldwork to undertake this project, supporting four researchers, two of whom are early career, was facilitated by the Richard West award.

Contemporary foraminifera at Churchhaven salt marsh

Churchhaven salt marsh is located in Langebaan Lagoon, a 15 km long, ~4 km wide embayment. Around the margin of the lagoon are granite headlands and Pleistocene-Holocene coastal dunes and aeolianites (Compton, 2001). The lagoon is connected to the open ocean through a tidal inlet which connects to Saldanha Bay. Whilst Churchhaven salt marsh was chosen for the study, the lagoon has extensive intertidal wetlands and mudflats located in the southeastern, southern, and western regions (**Fig. 3**).

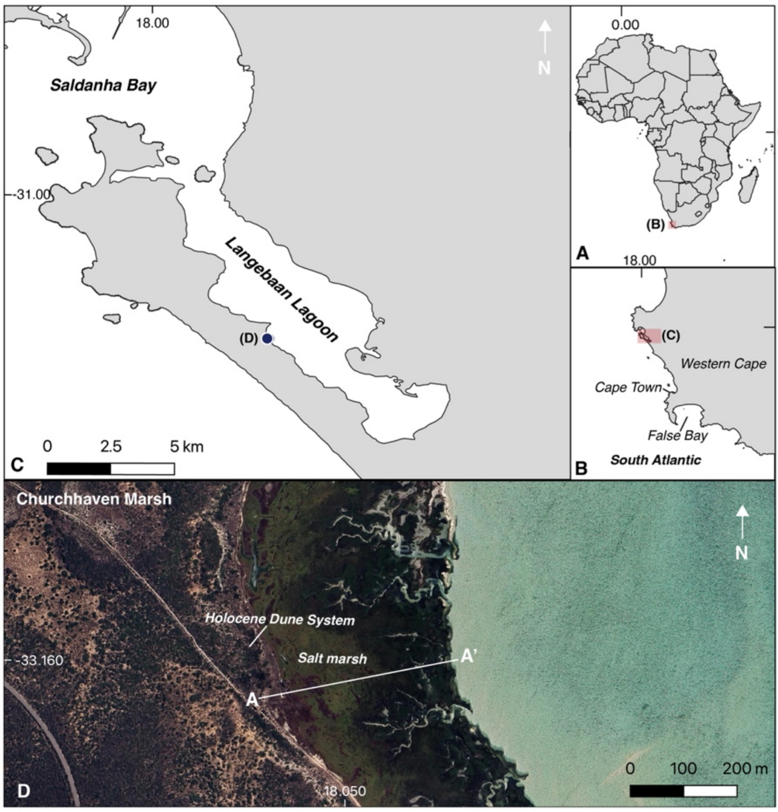

Figure 3. Map of Churchhaven showing regional overview (A,B), overview of the entire lagoon system and connection to Saldanha Bay (C) and Churchhaven salt marsh, showing the transect of modern samples from upland A to mudflat A' (D).

Thirty-eight surface samples were collected from upland to mudflat (**Fig. 4**) at 5 cm vertical intervals and stained with rose bengal immediately to identify live foraminifera. All elevations were related to mean sea level using manual surveying in combination with water level measurements and comparison to nearest tide-gauge data. Surface samples were wet sieved to retain the 63-500 μm fraction. Both live and dead foraminifera were enumerated. Identifications follow that of Williams et al. (2021), though distinctions are made between *Trochamminita salsa*, *Trochamminita irregularis* and *Pseudotrochamminita malcolmi* (King, 2021).

For live and dead assemblage analyses, samples with at least 20 live tests and 20 dead tests per sample are included in analyses. Test concentrations are generally higher for dead assemblages than live assemblages, particularly at higher elevations near the upper limit of marine influence (**Fig 4a**). Live tests have a higher concentration in the low marsh and mudflat – this may be due to dissolution of calcareous tests in dead assemblages. The total number of samples included in the cleaned data set is 16 (this number will increase as further samples are enumerated). On average, the most dominant species in the training set is *T. inflata* (average relative abundance of 39 % and 44 % in the dead and live assemblages respectively), followed by *M. fusca* (19% and 16 % respectively).

Relative average and maximum abundances of common species found in the modern data such as *Trochammina inflata*, *Entzia macrescens*, *Ammonia* spp. and *Quinqueloculina* spp.

are largely similar between live and dead assemblages (**Fig. 4b**). The only species exceeding 10 % abundance in live assemblages and not dead assemblages is *Bolivina spathulata*. Live and dead assemblages also have largely similar species responses to the environment, with *T. inflata*, *E. macrescens*, *Milliammina fusca*, *Ammonia* spp. and *Elphidium* spp. having a broadly unimodal distribution in both the live and dead data. *Quinqueloculina* spp. appears to respond linearly to elevation in both the live and dead assemblages, though the full species response curve may not have been captured (**Fig. 4c**).

The following description of the results will now focus exclusively on the dead assemblages (as these are deemed closest analogues to fossil material and are of most interest for sea-level reconstruction). **Fig. 4c** shows *E. macrescens* is the most abundant species between the upland zone and the high marsh (at the highest occurrence of foraminifera) where the vegetation is predominantly (woody) *Sarcocornia* (average relative abundance 14 %, maximum relative abundance 78 %). *Trochammina inflata* is sub-dominant near the upland border and is particularly dominant in the high-mid marsh (up to 78 %). Into the mid-low marsh, which is dominated by *Chenolea*, *Triglochin* and, at lower elevations, *Spartina*, *M. fusca* increases in abundance (average 19 % relative abundance, maximum 59 %). Below mean sea level, onto the mudflat, agglutinated species are replaced by common benthic salt marsh calcareous species such as *Ammonia* spp., *Elphidium* spp. and *Quinqueloculina* spp. These trends are also shown in **Fig. 4a** where species are broadly zoned by elevation (m MSL).

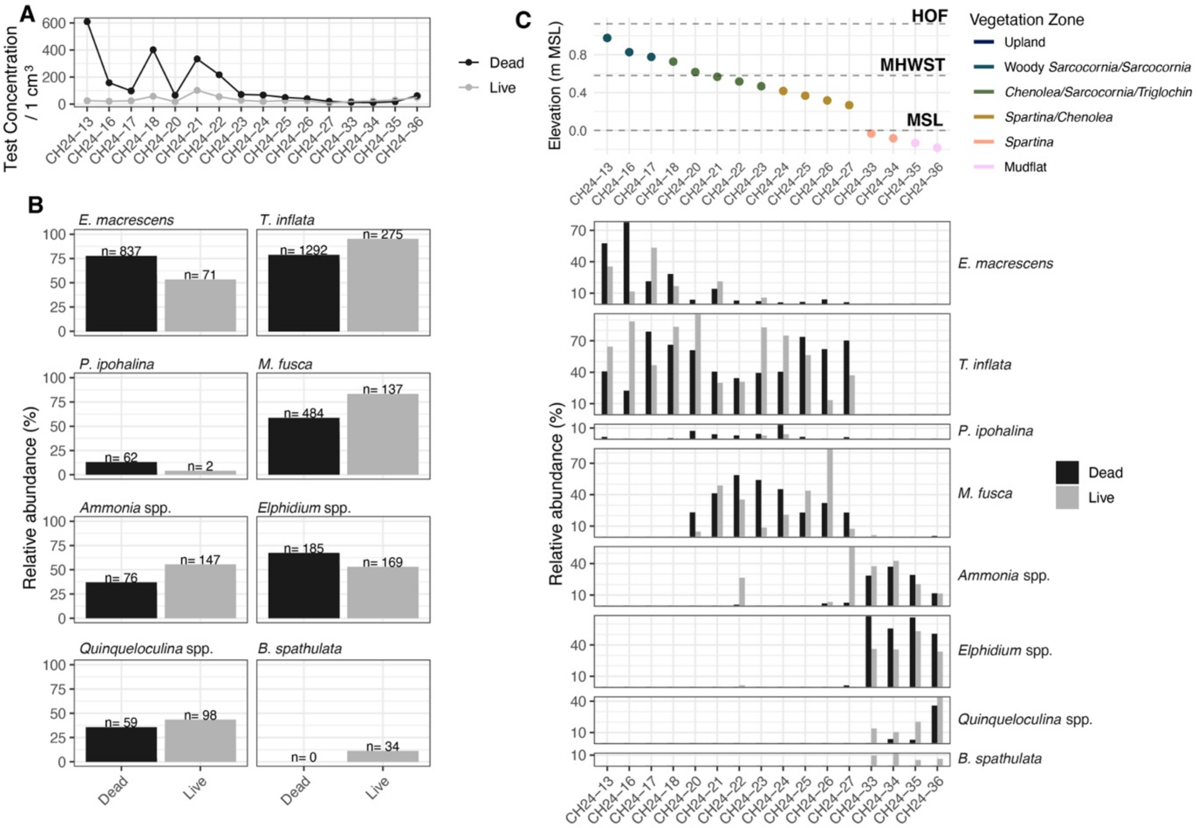

Figure 4. **A.** Test concentration of live and dead foraminifera from upland to tidal flat showing samples with total counts exceeding 20 individuals per sample and 10 % relative abundance. **B.** Relative abundance of live and dead foraminifera by species. **C.** Lateral distribution of live and dead benthic foraminifera at Churchhaven salt marsh from upland to mudflat. Mean High Water Spring Tide (MHWST) and Mean Sea Level (MSL) datums are indicated. Also shown is

the Highest Occurrence of Foraminifera (HOF) which signifies the upper limit of marine influence at the site.

To identify groupings within the modern dead assemblage, various clustering and ordination analyses are employed. Silhouette analysis identifies the optimal number of groups for partitioning around medoids clustering. This analysis indicates that the Churchhaven data are best grouped into five clusters, with an average overall silhouette width of 0.62 (where 1 indicates perfect classification of each sample into a cluster (**Fig. 5b**)). Within clusters, the greater the silhouette width, the more similar the samples are to each other. The foraminiferal assemblages within Cluster 2 (Si = 0.69) were identified as being most similar, while Cluster 1 was most disparate (Si = 0.55). This is likely due to the high relative abundance of *T. inflata* in Cluster 1 and its ubiquity across the elevational gradient, leading to more variability within the cluster (**Fig. 5a/c**). Though, overall, there is little difference between the average widths of all clusters. Clusters are grouped largely by elevation (cluster means: 1 - 0.87 m MSL, 2 - 0.89 m MSL, 3 - 0.39 m MSL, 4 - 0.49 m MSL, and 5 -0.13 m MSL; **Fig. 5c**), again showing the dominance of tidal inundation on species distribution. Non-metric multidimensional scaling ordination shows samples classify largely into two distinct groups in ordination space: salt marsh and mudflat. Within the salt-marsh space, samples can broadly be grouped into high marsh and mid-low marsh, with high elevation samples clustered around *E. macrescens* and *T. inflata* and mid-low elevation samples clustered around *M. fusca* and *Polysacammina ipohalina.*

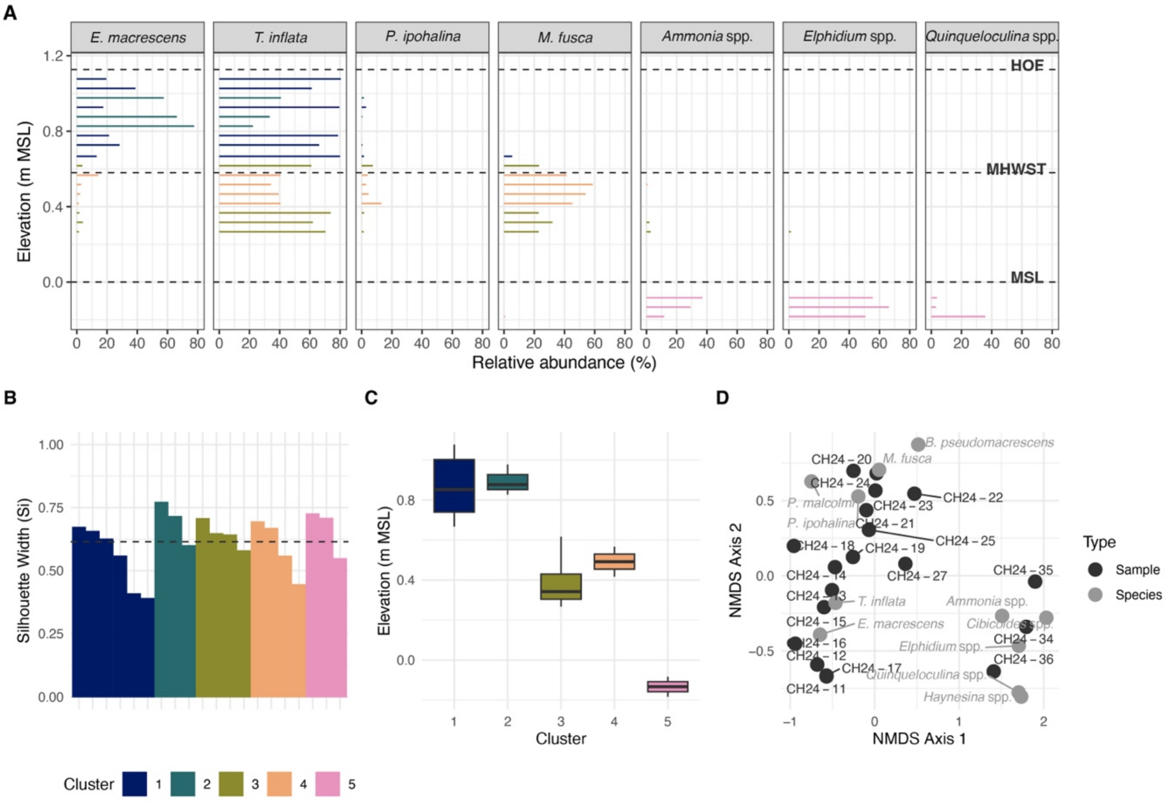

Figure 5. A. Modern dead assemblage foraminifera from Churchhaven marsh ordered by elevation and coloured by partitioning around medoids cluster analysis showing samples exceeding 50 individuals and with at least 10% abundance in at least one sample. Tidal datums are denoted by the dashed lines. **B.** Silhouette analysis showing partitioning around medoids analysis clusters, black dashed line shows average silhouette width across the

clusters. **C.** Box plot showing elevation ranges of foraminifera classified into each cluster. **D.** Non-metric multidimensional scaling ordination.

Comparison with other contemporary training sets

Agglutinated and calcareous benthic foraminifera found at Churchhaven are typical of those found in temperate salt marshes. Indeed, Scott et al. (2001) suggest that ~10 species of benthic foraminifera *e.g. T. inflata* and *M. fusca* are found ubiquitously globally. Foraminifera at Churchhaven have also been found elsewhere in the Southern Hemisphere, and in South Africa more specifically. For example, at Galpin's marsh located in the Eastern Cape, Strachan et al. (2015) identified 13 taxa. Similarly to Churchhaven, *T. inflata* and *E. macrescens* were found to dominate in the high marsh, with *M. fusca* increasing in abundance at lower elevations. *Entzia macrescens* is more dominant at Galpin's compared to Churchhaven, which may be reflective of the likely lower salinity environment at Galpin's compared to Churchhaven given the position of Galpin's marsh up-estuary. Largely similar calcareous species were also identified at Galpin's as at Churchhaven. Interestingly, Strachan et al. (2015) found that in the highest elevation samples near the upper limits of marine influence, *E. macrescens* exhibited the largest discrepancy between live and dead foraminifera, with higher relative abundances in the dead assemblages compared to live, which is replicated at Churchhaven. Strachan et al. (2015) attribute this to seasonal changes in the living distribution of foraminifera. At Churchhaven, *T. inflata* has larger live relative abundances at the highest elevations, which generally decrease with elevation. At Keiskamma salt marsh, also in the Eastern Cape, species diversity is lower, though similar dominant agglutinated and calcareous species are found as at Churchhaven (Strachan et al., 2017). The high marsh is also dominated by *T. inflata* and *E. macrescens*, however, overall relative abundances across the elevational gradient are dissimilar, with a higher relative abundance of *M. fusca* in the data set (the species often exceeds 50 % in each sample). A similar pattern is also observed at Knysna salt marsh (Western Cape) (Strachan et al., 2017), highlighting inter-site variability in foraminiferal composition along the coastline. This is likely driven by local environmental heterogeneity, for example, variations in climate, geomorphology, salinity, and sediment composition.

Elsewhere in the Southern Hemisphere, modern distributions of foraminifera have been analysed in Australia (*e.g.* Horton et al., 2003; Woodroffe, 2005; Callard et al., 2011; Gehrels et al., 2012; Williams et al., 2021; 2023), New Zealand (*e.g.* Southall et al., 2006; Gehrels et al., 2008; Hayward, 2014; Garrett et al., 2022; King et al., 2024) and South America (Newton et al., 2021). Foraminifera in these training sets have also been found to respond largely to frequency of tidal inundation, though again, local site dynamics affect the dominance of each species and their optima and tolerance within the tidal frame. Clustering of modern foraminifera by elevation, such as found at Churchhaven, is common across these studies, for example, in Australia (Williams et al., 2021) identified 3 distinct clusters in the training set, with partitioning around medoids analysis identifying a high-elevation, mid-elevation and low-elevation cluster. This pattern has not only been found in the Southern Hemisphere, but also in the North Atlantic region (Kemp et al., 2012; Walker et al., 2023). Again, this strengthens the utility of foraminifera as sea-level indicators, demonstrating their close relationship to tidal inundation and frequency.

Implications for high-resolution sea-level studies from South Africa

Identification of elevation-dependent ecological zones at Churchhaven suggests that salt-marsh foraminifera at the site are appropriate indicators for reconstructing Common Era sea-level change. Once further samples are enumerated to reach a target training set of at least 40 samples, a quantitative Bayesian transfer function (BTF) approach will be used to generate 'palaeomarsh surface estimates' *i.e.* X0 (**Fig. 2**). Preliminary analyses indicate that the BTF can reconstruct sea level at Churchhaven with decimetre-scale vertical precision, which is in line with other Common Era studies (Walker et al., 2021). Palaeo sea-level estimates will be combined with high-resolution chronological analyses, employing a suite of methods including: ^{14}C, ^{210}Pb, ^{137}Cs and $^{206}Pb/^{207}Pb$. Currently, while local Holocene sea-level variability can be resolved, sea-level reconstructions in South Africa are constrained by low-resolution chronologies, and sea-level index points have large indicative ranges (Compton, 2001; Strachan et al., 2014). This limits investigations of multi-annual–multi-decadal sea-level variability, making it challenging to resolve short-term fluctuations and ascertain driving mechanisms.

The use of foraminifera at Churchhaven will also be dependent on similarity between the modern and fossil data, as modern assemblages must be analogous for reliable reconstructions (Kemp and Telford, 2015). Churchhaven salt marsh is located in a marine protected area in an open embayment. This forms part of the West Coast National Park, gazetted in 1985. There is no indication that the site has been altered, or the local dynamics have changed (at least over the time period of interest to this study). Indeed, Compton, (2001) suggests the site has been largely unchanged since ~ 4.9 ka when present mean sea level was reached. This followed the Mid-Holocene highstand when the lagoon was flooded, with relative sea level to potentially up to 3 m above present. Pending modern analogue comparison, foraminifera will be used as palaeo sea-level indicators and will be supported by high-resolution lithostratigraphic and chronostratigraphic data to generate a sea-level reconstruction for the Langebaan area. This reconstruction will contribute to the growing, but limited, number of reconstructions from the Southern Hemisphere and will allow for a long-term investigation into (sub)decadal sea-level variability in the region. This work is critical for understanding the local–regional driving forces behind relative sea-level change, which is vital for projecting into the future sea-level changes and aiding with adaptation and mitigation policy.

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