Tidal distribution of foraminifera in Brooklands Lagoon, Canterbury, New Zealand

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I. Abstract
The February 2011 Christchurch earthquake caused widespread liquefaction and subsidence in Brooklands Lagoon, located just north of Christchurch. The shifts of major flora in the lagoon have been studied in Brooklands Lagoon; however, little is known about the various species of microfauna that inhabit the lagoon and the extent to which these foraminifera respond to shifts in tidal height, salinity, and sediment size. Samples were collected along a 200m east-west transect in the lagoon to establish an initial distribution of foraminiferal species, which paleontologists and ecologists can use to compare changes in foraminiferal distribution to after future seismic events.

II. Introduction
Due to their sensitivity to tidal height, salinity, and sediment size, benthic foraminifera have proven to be valuable indicators of past coseismic disturbances in wetlands (Hayward, 2007; Hayward et al., 1999b). There are very few dominant species of foraminifera that live in the brackish environments of New Zealand; however, through comparison to past surveys, they can help uncover evidence of fault ruptures and earthquakes (Hayward et al., 2007). Studies have shown that fossil foraminifera can serve as a baseline for estimating past relative vertical tectonic displacement in the Holocene along New Zealand coasts (Southall et al, 2006). Previously found associations of foraminifera species with salinity and tidal exposure can also aid in the detection of spatial changes within the lagoon (Figures 1 and 2).

Foraminifera on New Zealand’s coast have been extensively studied and often used as evidence for coseismic disturbances (Buzas et al, 2007; Reid et al., 2013); and the major flora across the lagoon has been mapped and quantified by Worner and Partridge (2008), who found that in comparison to the Avon-Heathcote Estuary just to the southeast of Christchurch, Brooklands Lagoon showed less variability in river marsh zones and more diverse habitats occurring in drier and sandier sequences of the marsh. Other studies of Avon-Heathcote show that tidal zones migrated landward as a result of subsidence, and that microfauna tend to be zoned by tidal elevation and therefore shift accordingly during seismic disturbance, whether it be uplift or subsidence (Reid, 2013).

Brooklands Lagoon, one of the northernmost suburbs of Christchurch (Figure 3), underwent a significant amount of liquefaction and subsidence in response to the February 2011 earthquake. The subsidence greatly altered the lagoon’s flora and fauna; but while the changes in flora have been studied (Worner and Partridge, 2008), no surveys of foraminifera species has been done. Therefore, little is known about which foraminiferal species inhabit Brooklands Lagoon, let alone how these foraminiferal microfauna respond to rapid changes in tidal height, salinity, and sediment character. The goal of this study is to determine the distribution of foraminifera species at various tidal heights within Brooklands Lagoon so as to provide a baseline to which paleontologists can compare distributions in the future should further seismic induced subsidence occur in this area.

III. Geologic Setting
The February 2011 earthquake (Mw 6.2) that hit Christchurch, New Zealand caused widespread damage and liquefaction both within the city and in its suburbs. It was the result of oblique-reverse slip along a northeast-southwest striking fault with a dip of about 69°, and an aftershock of the 2010 Darfield earthquake (Mw 7.1) that occurred to the east of Christchurch. The greatest slip occurred at only about 3 to
4 km depth, and vertical and horizontal ground movement registered up to 2.2g and 1.7g, respectively in the city center (Kaiser, 2012).

Brooklands Lagoon, about 800 meters across at its widest point and about 3 kilometers long, forms part of the mouth of the Waimakariri River in the Christchurch suburb of Brooklands (Figure 3), which is built on old sand dunes. After a period of tectonic activity in wetlands, geomorphological processes affecting the distribution of sediment sizes are known to continue occurring up to 100 to 200 years after tectonic activity ends (McFadgen and Goff, 2005), meaning Brooklands Lagoon is still very much susceptible to changes in the sedimentary environment. The combination of fine sands that make up the majority of sediment beneath Christchurch, combined with a generally high water table and anthropogenic reworking of the sediments, makes the Brooklands area particularly susceptible to liquefaction and lateral spreading during an earthquake (Kelland, 2013).

IV. Methods
4.1 Sample collection
Twenty-one sediment samples were collected from the top 3 to 5cm of sediment every 10 meters along a 200 meter tidal transect running east to west in Brooklands Lagoon; samples for foraminifera were also collected at the same spots. RTK survey equipment was used to mark the elevation and location the samples were taken at.

4.2 Sediment size analysis
Sediment size was analyzed using a Saturn Digisizer II at the University of Canterbury and binned into percent coarse sand, medium sand, fine sand, very fine sand, silt, and mud.

4.3 Foraminifera analysis
Foraminiferal samples were soaked in Rose Bengal (1g/L) for 24 hours to stain foraminiferal protoplasm (methods modified from Hayward et al., 2007 and Walton, 1952), which allowed for identification of live versus dead foraminifera. Samples were then rinsed through a 63μm sieve to remove clays and silts, and dried at 60°C. Samples F090, F100, F110, and F180 were also soaked in 10% hydrogen peroxide to remove excess plant material. Samples F000 and F120 were floated in LST heavy liquid to remove abundant denser materials. Both sets of samples were rinsed again and dried at 60°C. From each sample where it was possible, about 100 foraminifera were picked, mounted, identified, and counted by species, since this number is considered appropriate for statistical evaluation of estuarine microfauna (Hayward, 2007).

Samples without a significant number of specimens were removed, and the remaining counts were statistically analyzed using PAST software. Diversity indices were calculated to determine the evenness and dominance of foraminifera species along the transect, and a two-way Bray-Curtis cluster analysis was conducted to determine relatedness of the samples based on species diversity and richness indices.

V. Results
5.1 Sediment size analysis
Sediment size is largely silt with a moderate mud component across the transect (Figure 4). At 0m there is a small amount of coarse sand (~2%) and a spike in grain size to about 40% medium and fine sand. The amount of medium and fine sand peters out as distance along the transect increases.

5.2 Foraminifera species
Seven species of foraminifera were found: Milliammina fusca, Trochamminita salsa, Ammotium fragile, Trochammina inflata, Haplophragmoides wilberti, Jadammina macrescens, and Elphidium
excavatum. It is clear from Figure 5 that samples taken further offshore contain much higher numbers of *Milliammina fusca*, although most samples are either dominated by that or *Trochamminita salsa*.

Foraminifera were abundant enough for statistical analysis in about half of the samples, and typically in the sites with finer grain sizes (silt and smaller). The correspondence plot (Figure 6) shows three distinct clusters of samples, with F000 to the far top-left; F070 to the bottom-left, and the remaining samples with statistically significant numbers of foraminifera all clustered on the right. Dominances in the major cluster range from 0.50 to 1.00, with evenness ranging from 0.43 to 1.00. F000 shows a dominance of 0.49 and an evenness of 0.87; F070 shows a dominance of 0.32 and an evenness of 0.71.

VI. Discussion

Similar to Berger (2014), there does not appear to be a statistically significant relationship between sediment size and foraminifera abundance and diversity. However, the sediment size graph and transect profile (Figures 4 and 5) do reveal that as elevation and sediment size decrease moving further west into the lagoon, the diversity of foraminifera decreases as well. The correspondence plot (Figure 6) also shows a tight clustering of samples taken past 080m on the transect, most of which show dominance by *Milliammina fusca* greater than 0.76, with only one (F190) having a lower dominance (D=0.50).

There was a limited abundance of foraminifera between sites F000 and F110, but samples F000 and F070 still sit quite noticeably outside of the large cluster (Figure 6). Each has a relatively low dominance (D=0.49 and D=0.32, respectively), indicating that these areas do not tend to be dominated by any one particular species. However, the transect profile shows that these two samples contain very different numbers of various species, which is likely an effect of the decrease in elevation and sediment size from F000 and F070 (Figures 4 and 5).

F050 and F080, which both lie slightly outside the single large cluster (Figure 6) appear relatively similar in terms of dominance and evenness, but both samples were taken from areas with higher elevation and larger sediment size than the other samples within the cluster. It should also be noted that samples F090, F100, F110, and F180 may all distinctly lacking in foraminifera abundance due to having been soaked in hydrogen peroxide, which could have destroyed the foraminifera in those samples.

VII. Conclusion

The single large cluster (Figure 6) is dominated by *Milliammina fusca*, which seems to correspond to a decrease in sediment size. Sediment size and tidal height differences may also be the cause of the significant differences in species distributions between samples F000 and F070. Samples on the eastern half of the transect show lower abundances of foraminifera; though probably partially due to soaking some samples in hydrogen peroxide, this could be the result of a shift in tidal environment, and it would be beneficial to recollect samples at this location for further analysis.

Regardless, the data found about foraminifera distribution in Brooklands Lagoon provides a baseline that will allow paleontologists to make inferences about how foraminifera species distribution changes in response to subsidence. In conjunction with a plant survey taken along this and other transects in Brooklands Lagoon done by Ashley Ratigan and the analysis of a core taken at the 110m mark along the transect done by Emma Schlam, the foraminifera data found will allow for a more quantitative and expansive assessment of how flora and fauna respond to local subsidence and whether or not their responses are uniform across the lagoon.

VIII. Acknowledgements

Thanks to Emma Schlam and Ashley Ratigan for their assistance in collecting data at Brooklands Lagoon, and to Chris Grimshaw for helping with the sediment sizing and foraminifera sample separation.
IX. References

Berger, K., & Reid, C. M. (2014). Foraminifera species distribution and geochemistry of Lyttleton Harbour, Canterbury, NZ.


McFadgen, B. G., & Goff, J. R. (2005). An earth systems approach to understanding the tectonic and cultural landscapes of linked marine embayments: Avon-Heathcote Estuary (Ihutai) and Lake


## X. Appendix

### Tables

<table>
<thead>
<tr>
<th>Sample</th>
<th>SED 000</th>
<th>SED 050</th>
<th>SED 070</th>
<th>SED 080</th>
<th>SED 120</th>
<th>SED 130</th>
<th>SED 140</th>
<th>SED 150</th>
<th>SED 160</th>
<th>SED 170</th>
<th>SED 180</th>
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<tr>
<td>% fine sand</td>
<td>3.9</td>
<td>2.4</td>
<td>3.8</td>
<td>1.7</td>
<td>4.3</td>
<td>3.4</td>
<td>2.1</td>
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<td>2.1</td>
<td>3.3</td>
<td>2.7</td>
<td>2.2</td>
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Table 1. Percentage of fine sand as measured by the Saturn Digisizer II for the samples that had statistically significant numbers of foraminifera.

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<tr>
<th></th>
<th>F000</th>
<th>F050</th>
<th>F070</th>
<th>F080</th>
<th>F120</th>
<th>F130</th>
<th>F140</th>
<th>F150</th>
<th>F160</th>
<th>F170</th>
<th>F180</th>
<th>F190</th>
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<tr>
<td>Dominance</td>
<td>0.49</td>
<td>0.69</td>
<td>0.32</td>
<td>0.64</td>
<td>0.98</td>
<td>1.00</td>
<td>0.98</td>
<td>0.89</td>
<td>1.00</td>
<td>0.76</td>
<td>0.82</td>
<td>0.50</td>
<td>0.79</td>
</tr>
<tr>
<td>Evenness</td>
<td>0.60</td>
<td>0.47</td>
<td>0.71</td>
<td>0.51</td>
<td>0.53</td>
<td>1.00</td>
<td>0.53</td>
<td>0.43</td>
<td>1.00</td>
<td>0.52</td>
<td>0.69</td>
<td>0.55</td>
<td>0.72</td>
</tr>
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</table>

Table 2. Dominance and evenness as calculated by PAST software for the foraminifera samples that had statistically significant numbers of foraminifera.
Figure 1. Distribution of ten brackish-water foraminiferal associations with respect to salinity and tidal exposure and their relationship to intertidal vegetation habitats. EHWS = extreme high water spring; MHWS = mean high water spring; MHW = mean high water; MSL = mean sea level and mid-tide level; MLW = mean low water (modified from Hayward et al., 1999a).
Figure 2. Schematic histograms summarizing the distribution of maximum relative abundance of common benthic taxa with decreasing tidal exposure (left) and increasing salinity (right) in sheltered brackish-water environments in New Zealand (taken from Hayward et al., 1999a).
Figure 3. Map of the transect used to sample for sediment and foraminifera in Brooklands Lagoon. Yellow dots represent transect location. Star in inset shows the location of Brooklands Lagoon in relation to Christchurch.

Figure 4. Sediment size data from each sample site along the transect, expressed as percentages of coarse sand, medium sand, fine sand, very fine sand, silt, and mud.
Figure 5. Graph of the 200m transect elevation profile, with east at 0 and west at 200. Pie charts indicate foraminiferal distributions along the transect, with $n$ being the number of foraminifera from each sample site, and asterisks indicating which samples were used in statistical analysis of species distribution. No foraminifera were found at site 100. Modern plant distributions based on a separate plant survey taken the day of sampling are also included. The location of the core used in Emma Schlam’s project is denoted by the red circle.

Figure 6. Correspondence plot with distinct clusters circled. Calculated dominance and evenness values are given for samples F000, F050, F070, and F080; a range for these values for the remaining statistically significant samples shown on the plot are given above the right-most circle.