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Short-Term Behavioural Responses of Selected Benthic Invertebrates Inhabiting Muddy Habitats to Burial by Terrestrial Clay

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Short Term Behavioural Responses of Selected Benthic Invertebrates Inhabiting Muddy Habitats to Burial by Terrestrial Clay

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1 Executive Summary

The objective of this work was to determine short term behavioural responses of macrofauna, living in muddy sediments, to the deposition of a slurry of terrigenous clay. This report extends work on sandy sediments (Norkko et al., 1999) by presenting likely effects of clay deposition on mudflats found in the upper reaches of Okura estuary.

Laboratory experiments were conducted, on seven types of macrofauna common in the muddy sediments of Okura estuary. These taxa were, the small bivalve, *Nucula hartvigiana*, the snapping shrimp, *Alpheus* sp., the mud snail, *Amphibola crenata*, polychaete worms from the family Nereidae, *Aquilaspio aucklandica* and *Boccardia* sp. from the family Spionidae and Oligochaeta.

A clay slurry was added to cores containing sediment and animals, at depths of 0, 0.5, 1.0, 1.5, 3.0, 6.0, and 9.0 cm. The animals were left to live in the sediment for either 24, 72 or 144 h.

Chemical profiles of cores were analysed using vertical voltammetry immediately following the deposition of the clay slurry. Within 1 hour of adding the clay, the original sediment had become anoxic, completely changing the original biogeochemical vertical profile.

With clay layers of 0.5 - 1.5 cm thickness, the polychaetes and Oligochaeta were able to move into the clay layer. The snapping shrimps and snails were able to move through the clay to the surface. In cores with clay layers of 3.0 cm and greater, only the highly mobile snapping shrimps were able to move through to the surface. The slower snails and bivalves withdrew into their shells and the polychaetes suffered high mortality. Results for the bivalve *Nucula* were consistent regardless of clay thickness with the fitness of these bivalves decreasing with time buried.

In general, levels of stress and mortality of the macrofauna increased with time, probably due to reduced access to food and oxygen at the surface of the clay and the changing chemical composition of the original sediment. Larger, more-mobile animals were less affected than small and slow moving ones.

This work demonstrates the potential for significant ecological change as a result of catastrophic deposits of terrigenous clay in the upper reaches of Okura estuary. It confirms the suggestion made by Norkko et al. (1999), that clay layers less than 2.0 cm thick are less likely to impact on the whole community.

2 Introduction

This report presents information on the potential threats to the ecosystem in Okura estuary that result from the deposition of flood-borne sediments. It is an extension of the research presented by Norkko et al. (1999) entitled 'Ecological effects of sediment deposition in Okura estuary'.

One of the objectives of the research by Norkko et al. (1999) was to determine the critical thickness of sediment and coverage time that would produce either sub-lethal or lethal effects on animals living in the sediment. In their report they described the main habitats within Okura estuary and broadly described the benthic communities. In laboratory experiments they observed the ability of selected taxa to surface through different thicknesses of terrigenous clay and/or survive short term burial. Using these results and field experiments, they provided an ecological assessment of the potential effects of sediment deposition on the macrobenthic communities within two habitats in the estuary.

The aim of this study was to extend the information provided in Norkko et al. (1999), with data on the responses of macroinvertebrates adapted to living in muddy sediments. Norkko et al. (1999) specifically state that they did not conduct experiments reflecting conditions in the upper estuary and mangroves, but they make the point that these areas are more likely to experience an 'event'. Their reason for focusing on sandflat taxa was to obtain a wide variety of test organism responses. This is because sandflat habitats usually provide a far more diverse assemblage of organisms than muddier upper estuary habitats and animals living in sandy sediments may be less able to cope with deposits of fine sediments. Thus they predicted that animals dwelling in sand would exhibit a wider variety of sensitivity and responses to changing conditions.

2.1 Experimental design

2.1.1 Depth of added sediment

Six different clay thicknesses were used in the lab experiments (0.5, 1.0, 1.5, 3.0, 6.0 and 9.0 cm). These were chosen based on the results of lab experiments conducted by Norkko et al. (1999). The three larger depths of clay (3.0, 6.0 and 9.0 cm) were the same as those used by Norkko et al. (1999). They were chosen for the following reasons. The largest depth of 9.0 cm has previously been observed in an estuary. The smallest depth of 3.0 cm was chosen to correspond with the largest bivalves observed in the estuary and also matches the depth produced by natural sedimentation events observed in Okura (Hewitt et al., 1998). The 6.0 cm depth was chosen because it was an intermediate between the other two.

The smaller depths (0.5, 1.0, 1.5 cm) were chosen to provide more information on the sublethal effects of clay on macrofauna and to test the prediction made by Norkko et al. (1999) that clay depths of less than 2.0 cm would not impact on the whole community.

2.1.2 Taxa used in aquarium experiments

The seven taxa used in this experiment are common taxa observed in the upper reaches of Okura estuary. They were expected to be more successful at coping with a deposition of clay than those taxa from sandy areas because they live in the finer, more anoxic sediments associated with muddier areas.

The small bivalve *Nucula hartvigiana* is normally observed close to the surface at the low tidewater level. Generally bivalves are considered tolerant to impacts such as sediment deposition (Kranz, 1972) although there are differences in sensitivity due to size, anatomy and life history characteristics of individual taxa. They usually react by moving to the sediment surface or alternatively they close up their shells, switch to anaerobic metabolic pathways and wait for conditions to improve. This second strategy is good for short term impacts but it is very energy consuming. Over time it can reduce fitness of an individual and increase their susceptibility to other sources of mortality such as predation and disease (Norkko et al., 1999).

Snapping shrimp, *Alpheus* sp., like crabs, are highly mobile and are very well adapted to burrowing in soft, muddy sediments. Because of this they were expected to cope well with the addition of clay. These shrimp scavenge on the surface at high tide and then retire into their burrows as the water drains from the estuary. In areas with reduced wave action and storm activity they have an important role as bioturbators, mixing the fine sediments.

Amphibola crenata is a slow moving, deposit feeding gastropod that is common on high intertidal mud flats and mangroves. Like bivalves, they are a food source for larger animals such as fish and birds and make up an important component of kiamoana for local iwi.

The polychaete worms Nereidae, *Aquilaspio aucklandica* and *Boccardia* sp. are common in muddy sediments. They are mobile but are not expected to cope well with the deposition of clay, especially over longer periods of time (6 days or more).

3 Methods

3.1 Biological experiments

A series of aquarium experiments were conducted to test the short term behavioural responses of seven types of macrofauna, commonly observed in the muddier substrates of an estuary, to the deposition of terrestrial silts and clay. These animals were selected because they are relatively abundant on the mudflats high up the Okura estuary. They all differ in their degree of mobility and modes of feeding and hence in their expected short-term responses to the deposition of clay and silt.

All animals and sediment were collected from Okura estuary and transported back to the laboratory within 3 hours of collection. Only individuals in good condition were used. All experiments were conducted in a controlled temperature room at 18 °C with a 9:15 light:dark period.

A series of small individual aquaria were filled in the field with a plug of natural muddy sediment. Great care was taken to create as little disturbance as possible to the sediment plug and no efforts were therefore made to remove any of the original fauna from the sediments. Muddier substrates contain higher level of naturally occurring toxic chemicals, such as sulphides, than sandier ones. If disturbed, these toxins are released into the water and can negatively affect animals on the sediment surface.

The larger animals were tested separately and added to the cores in the laboratory (*Nucula*, *Amphibola*, *Alpheus*), were placed on the surface of the core in each aquaria and left to burrow and acclimatise for 24 hours. Nereidae were placed in the cores and left to burrow immediately after collection in the field, but before the addition of water. The smaller taxa, *Aquilaspio*, *Boccardia* and the Oligochaeta were already resident in the plug when it was collected.

Individual aquaria were placed in large water baths (12 per bath) with the water oxygenated by air pumps. After 24 hours the water in the water baths was changed to remove any toxins released due to disturbance of the sediment during collection and transport. Animals in each aquaria that had showed no movement were replaced with healthy individuals and allowed to burrow.

The number of individual animals used per core differed with each test taxa. For *Amphibola*, two individuals were used in every core (160 total), while for *Alpheus* only one individual was used as this was closer to their natural density in the field. Two *Nucula* were added to each core at the beginning of the experiment, but were so abundant in the sediment where the cores were collected, that every individual harvested in each core was recorded and included with the original test individuals (463 individuals in total).

Nereidae worms were relatively delicate and hard to collect undamaged, so only 1 individual per core was used and the number of replicates of each treatment were

reduced. During the Nereidae experimental run, as each core was harvested, every worm in the core was identified, counted and included in the analysis of the experiment.

The clay/silt slurry was collected from a settling pond in Howick, South Auckland. A lack of rain at the time of the experiment prevented sediment collection from ponds in the Okura area. However the sediment composition from the two areas was basically very similar. They are both a mix of yellow/brown clays and silt. Particle analysis was conducted on the clay/silt slurry using a Galai cis-100 rapid sediment analyser. The size of particles in the slurry ranged from 0.1 – 200.0 microns, with a mean of 0.96 microns (± 1.14 microns standard deviation).

A layer of clay slurry (water content ~50%) was added to each aquaria, at depths of 0.5, 1.0, 1.5, 3.0, 6.0 or 9.0 cm, except for those designated as controls.

For the depths 3.0, 6.0 and 9.0 cm, there was a total of five water baths each containing three replicates of each treatment (either 0, 3.0, 6.0, or 9.0 cm of clay). Separate replicates of each treatment were randomly sampled after 1, 3 and 6 days (24, 72, and 144 h). All seven taxa were tested at these depths.

For the smaller depths, 5 replicates of each treatment (either 0, 0.5, 1.0, 1.5 cm) were harvested only after 144 h for effects on *Amphibola* and *Nucula*. Only six Nereidae were collected so there was one replicate at depths of 0 cm and 1.5 cm and two replicates at the intermediate depths of 0.5 cm and 1.0 cm.

At the end of the experiment the number of animals lying on the surface of the clay layer, the position animal in the core, and mortality were measured in each aquaria. Any evidence of burrowing or movement by the animal within the core was also noted.

As a measure of recovery, *Nucula* and *Alpheus* were placed on muddy sediment from Okura and their reburial rates were observed over a 120-180 minute period immediately following their extraction from the treatments. Reburial rates are a standard measure of condition because burying is a natural response for most bivalve taxa and sub-lethally stressed animals remaining on the sediment surface are vulnerable to predators (Norkko and Bonsdorff, 1996).

For the snail, *Amphibola*, the time taken for an individual to re-orientate from an upside down position was recorded over a 210-300 minute period. Animals from each core were placed on shallow dishes of muddy sediment collected from Okura. All sediment used to measure reburial rates had been previously sieved on a 1 mm sieve and kept at 1°C until required.

3.2 Statistical analyses

To assess the significance of differences in the rates of mortality of Nereidae in cores with different depths of clay and also for different experimental periods, analysis was done on presence/absence in each core for the clay depths 3.0, 6.0 and 9.0 cm. We used a regression model with a binomial error structure and a canonical link function using SAS software. For the smaller clay depths (depths less than 3.0 cm) no statistical

analysis was done on the number of worms recovered because of low replication. For *Nucula*, *Amphibola* and *Alpheus* and the other worms, the responses were quite obvious and thus no statistical test was needed to interpret the results. These results were examined graphically.

3.3 Chemical analysis

Chemical analysis was conducted on sediment from Okura, following the deposition of a clay slurry over the experimental plugs from Okura. Four small aquaria each with either 0, 3.0, 6.0 or 9.0 cm of clay, were arranged in a water bath, as described above for the biological experiments. Chemical changes were measured in one position over time in the sediment by voltammetry, using a gold amalgam probe according to the method of Brendel and Luther (1995). Free porewater manganese (Mn^{2+}), iron (Fe^{2+}), sulphide (S-II) and oxygen (O_2) were each measured immediately after, as well as 24, 72, and 144 h after the clay was added. These elements provide a useful measure of sediment redox and thus provide a measure of the biogeochemical environment the animals experience when buried. This analysis was repeated in the presence of *Amphibola* (2 snails) and Nereidae (1 worm).

4 Results

4.1 Biological Experiments

4.1.1 *Nucula*

Nucula used in this experiment had shell widths ranging from 1.8 to 9.1 mm, with a mean of 4.9 mm (± 1.6 mm standard deviation).

In the experiments with 3.0, 6.0 and 9.0 cm of clay, no *Nucula* were observed on the surface of the clay after 24 h, however a number of small surface holes and tubes were observed. These were most probably made by *Boccardia* within the muddy sediment. Approximately 85 % of *Nucula* harvested from the treatment cores were buried at a depth of 5 mm in the muddy sediment. The rest were buried deeper within the core. After 72 h, most *Nucula* in the treatment cores were found at the muddy sediment/clay interface, however a few individuals in each core had migrated up into the bottom 10 mm of the clay layer. After 144 h, almost all *Nucula* in the treatment cores were observed in the top 10 mm of the muddy sediment below the clay layer.

All *Nucula* in the control cores had buried to depths of 5 mm or greater in the muddy sediment and remained at this depth over the course of the experiment.

The same results were observed in the cores with 0.5, 1.0 and 1.5 cm of clay. There were no individuals found on the clay surface. Most *Nucula* were harvested in the top 10 mm of the original muddy sediment. In a few instances some individuals had migrated up into the clay layer, but this did not appear to be related to the depth of clay in that core.

4.1.2 Reburial rates

Nucula from the control cores were more likely to rebury than those from the treatment cores on all times (Fig. 1). For the first 2 sampling times there was no consistent differences between numbers reburying in the different treatments, however reburial rates were slower with increased clay depth (Fig. 2).

By the end of the experiment *Nucula* were less successful at reburial and took longer to rebury than those harvested after 24 or 72 h, regardless of clay depth (Fig. 1 & 2). *Nucula* from the controls were more likely to rebury faster than those from the clay treatments. After 144 h, 70 % of the *Nucula* from the control had reburied after 150 min, whereas only 20 % had reburied in the 3.0 cm treatment, 15 % in the 6.0 cm treatment and 10 % in the 9.0 cm treatment (Fig. 2).

Figure 1: Reburial rates of *Nucula* into muddy Okura sediments recorded over a 210 minute period. Each bar represents the mean (\pm SE) of 5 replicate cores each with 0, 3.0, 6.0, and 9.0 cm of clay. N = 393 individuals.

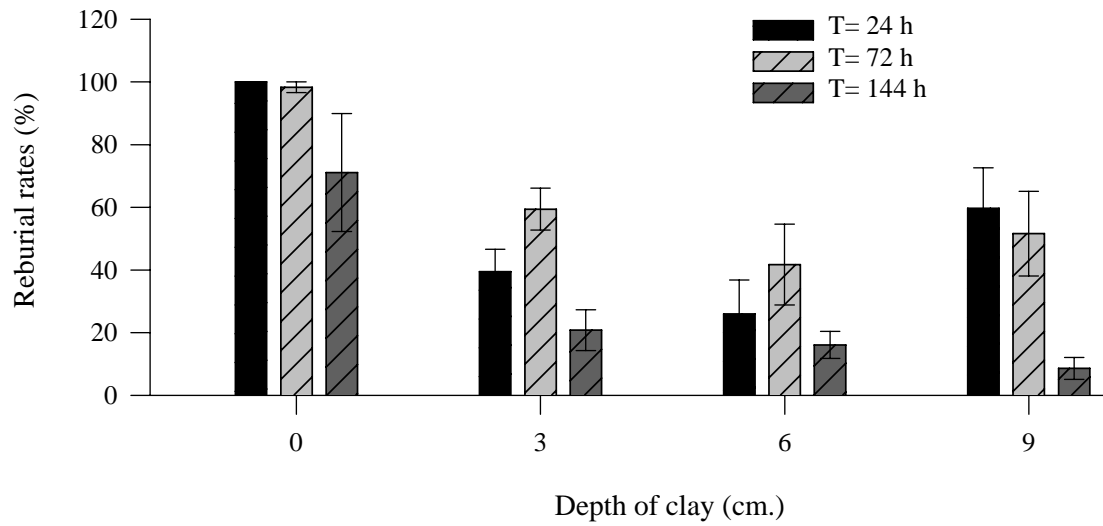


Figure 2: Reburial rates for *Nucula* into muddy Okura sediments calculated as percentages over time. To aid interpretation each line connects means of 5 replicates of cores per time. N = 393 individuals.

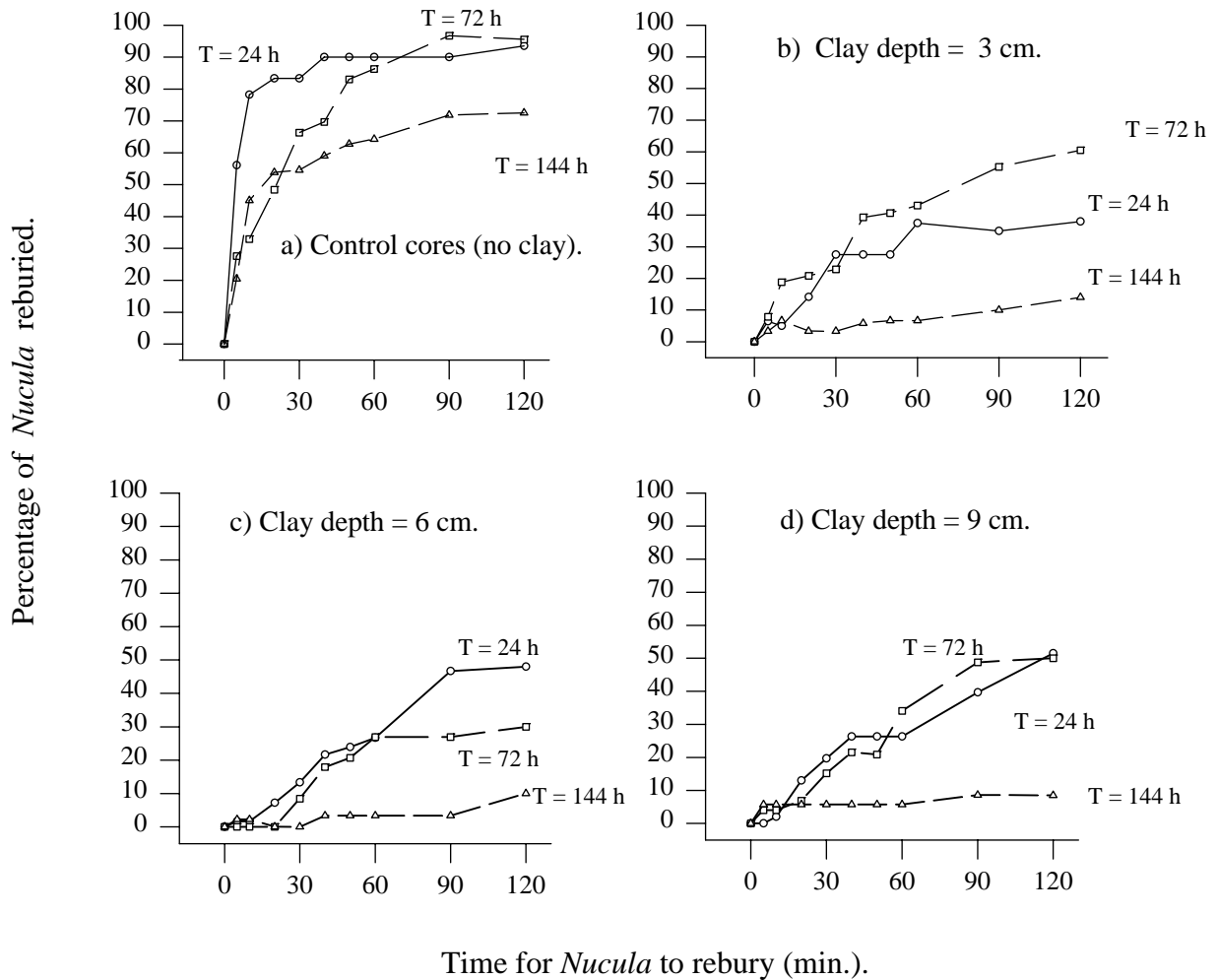


Figure 3: Reburial rates of *Nucula* into muddy Okura sediments, recorded over a 210 minute period. To aid interpretation each line connects means (\pm SE) of 5 replicate cores each with 0, 0.5, 1.0, and 1.5 cm of clay after 144 h. N = 70 individuals.

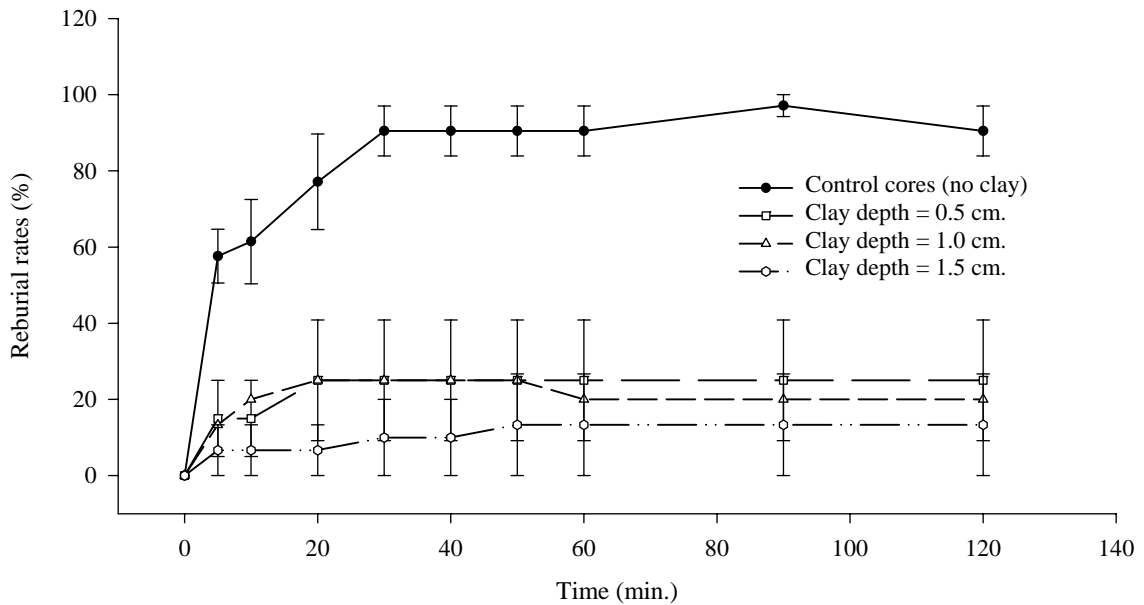


Figure 3 shows the reburial rates of *Nucula* into muddy sediments following the harvesting from cores with 0.5, 1.0 and 1.5 cm of clay after 144 h. This clearly shows that individuals from the control cores were much quicker to rebury than those from cores with clay. *Nucula* from cores with the most clay (1.5 cm) were the least successful at reburial. Table 1 shows that *Nucula* from cores with 0.5, 1.0 and 1.5 cm of clay were more successful at reburial than those from cores with 3.0, 6.0 and 9.0 cm that were harvested after 144 h.

Table 1: Reburial rates of *Nucula* from all seven clay depths after a 120 minute period.

Clay depth (cm.)	0	0.5	1.0	1.5	3.0	6.0	9.0
<i>Nucula</i> reburied (%)	90.9	25.7	20.7	14.2	14.0	10.0	8.5
No. individuals	18	15	18	19	28	31	31

4.1.3 Amphibola

Amphibola used in the aquaria had shell widths ranging from 8.0 to 26.0 mm, with a mean of 19.8 mm (\pm 3.4 mm standard deviation). *Amphibola* normally occur on top of the sediment and all the snails in the controls were found on the surface of the sediment. In the experiments with 0.5, 1.0 and 1.5 cm of clay about 75 % of the *Amphibola* were observed on top of the clay layer after 144 h. All individuals recovered from both the control cores and the treatment cores were alive. In the greater clay depths, the *Amphibola* in all treatment cores failed to burrow up through to the surface of the clay. Around 80 % were found on the old surface of the muddy sediment. These had withdrawn into their shells. The rest were stuck to the side of the aquaria 2 cm up into the clay layer. In the control cores, there were no snails observed stuck to the aquaria walls.

After 144 h, 25 out of a total 30 of *Amphibola* from the clay treatments were open and half out of their shells. These individuals failed to withdraw into their shells.

4.1.4 Reorientation

Amphibola from the controls were more mobile than those from the clay treatments. The *Amphibola* in the control cores flipped from their back onto their foot within 105 minutes, i.e. in less time, than the *Amphibola* from the cores with clay. In the cores with 3.0, 6.0 and 9.0 cm of clay this is especially clear after 72 and 144 h (Fig. 4).

Figure 4: Reorientation of *Amphibola*, 72 and 144 h after the clay was added. Animals were observed over a 300 minute period. Each bar represents the mean (\pm SE) of 10 replicate cores containing either 0, 3.0, 6.0, and 9.0 cm of clay. N = 120 individuals.

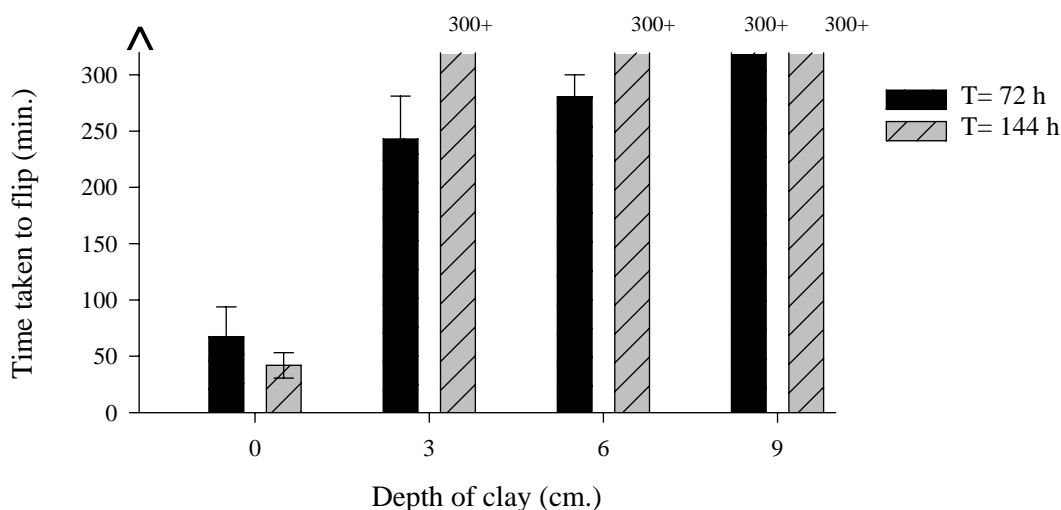
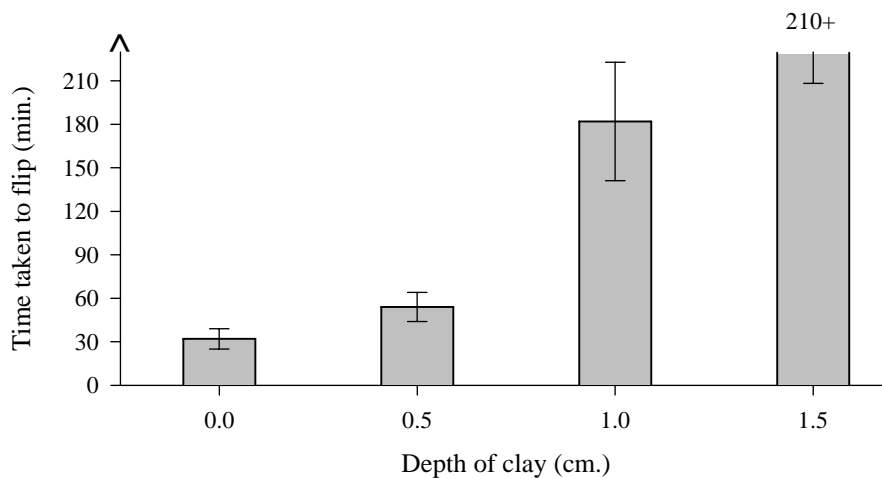


Figure 5 shows that *Amphibola* from the cores with 0.5 cm of clay were significantly quicker at reorientation than those that had been smothered by 1.0 cm of clay. Almost all individuals from the cores with 1.5 cm of clay failed to reorientate during the 210

minute period of observation. *Amphibola* from the cores with 0.5, 1.0 and 1.5 cm of clay reorientated in less time and were more active than those from cores with 3.0, 6.0 and 9.0 cm of clay, after 144 h.

Figure 5: Reorientation of *Amphibola* 144 h after the clay was added. Animals were observed over a 210 minute period. Each bar represents the mean (\pm SE) of 5 replicate cores containing either 0, 0.5, 1.0, and 1.5 cm of clay. N = 10 individuals per clay depth.

Alpheus:



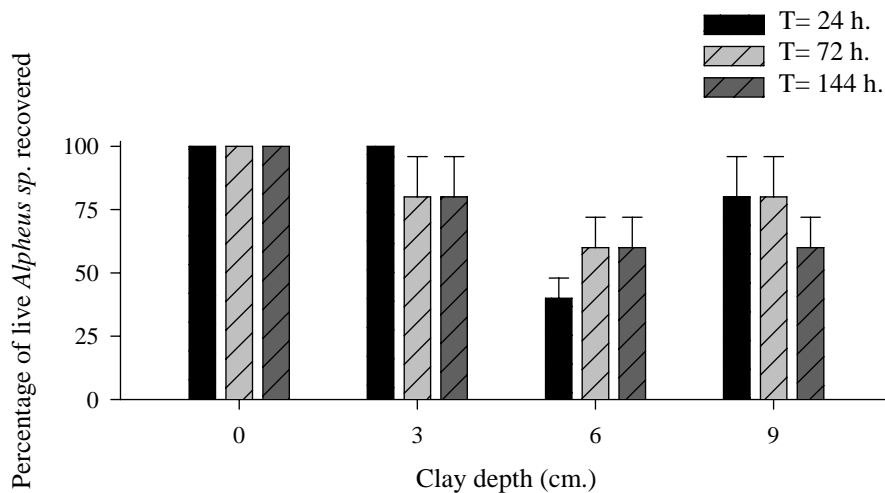
The mean length of *Alpheus* (snapping shrimp) was 30.9 mm (\pm 9.4 mm standard deviation). All *Alpheus* in the control cores were recovered alive and all had made deep burrows in the sediment. The live *Alpheus* in the treatment cores were very active, all were found on the surface of the clay. There were no burrows observed in the clay layer, probably because the clay was quite sloppy and burrows could not be constructed or had collapsed.

Figure 6 shows the numbers of live *Alpheus* removed from the cores over time. After 24 h, four *Alpheus* (out of 20) were found dead in the treatment cores. After both 72 h and 144 h, a further five *Alpheus* were found dead. Dead *Alpheus* were found evenly throughout the different clay depths. Most of the dead *Alpheus* were found on top of the clay layer or somewhere within it.

4.1.5 Reburial rates

Live *Alpheus* from both the control and treatment cores reburied in fresh sediment with no clay within 180 min. There was no difference in the reburial rates of *Alpheus* from different treatments. Live individuals that were removed from cores with clay all appeared very active.

Figure 6: Percentage of live *Alpheus* recovered from the cores after 24, 72 and 144 h. Each bar represents the mean (\pm SD) of 5 replicate cores containing either 0, 3.0, 6.0, and 9.0 cm of clay. N = 60 individuals.



4.1.6 Nereidae

The Nereidae showed little movement within cores covered by 3.0 cm or more of clay during the experimental period. Out of a total of 42, only four individuals were observed in the clay layer. The rest were at surface of the muddy sediment. In the lesser clay depths, Nereidae were observed within the clay layer.

In the experiment with 3.0, 6.0 and 9.0 cm of clay, after 24 h only one Nereidae (out of 12) had died, from a core with 9.0 cm of clay. After 72 h, two Nereidae were found dead, both from a core with 6.0 cm of clay. After 144 h, half the Nereidae had died. Most of the mortalities were from cores with 3.0 and 6.0 cm of clay. The remaining six individuals recovered from the clay after 144 h were sluggish and appeared stressed. All worms that were recovered from the control cores were alive and active except for one individual recovered after 144 h. Statistical analysis for this experiment shows the depth of clay in each core had significant effect (95 %, $p = 0.0067$) on the number of Nereidae found alive after 24, 72 and 144 h.

In the Nereidae cores with 0, 0.5, 1.0 and 1.5 cm of clay, there was one mortality (out of six) after 144 h. This mortality was from a core with 1.5 cm of clay.

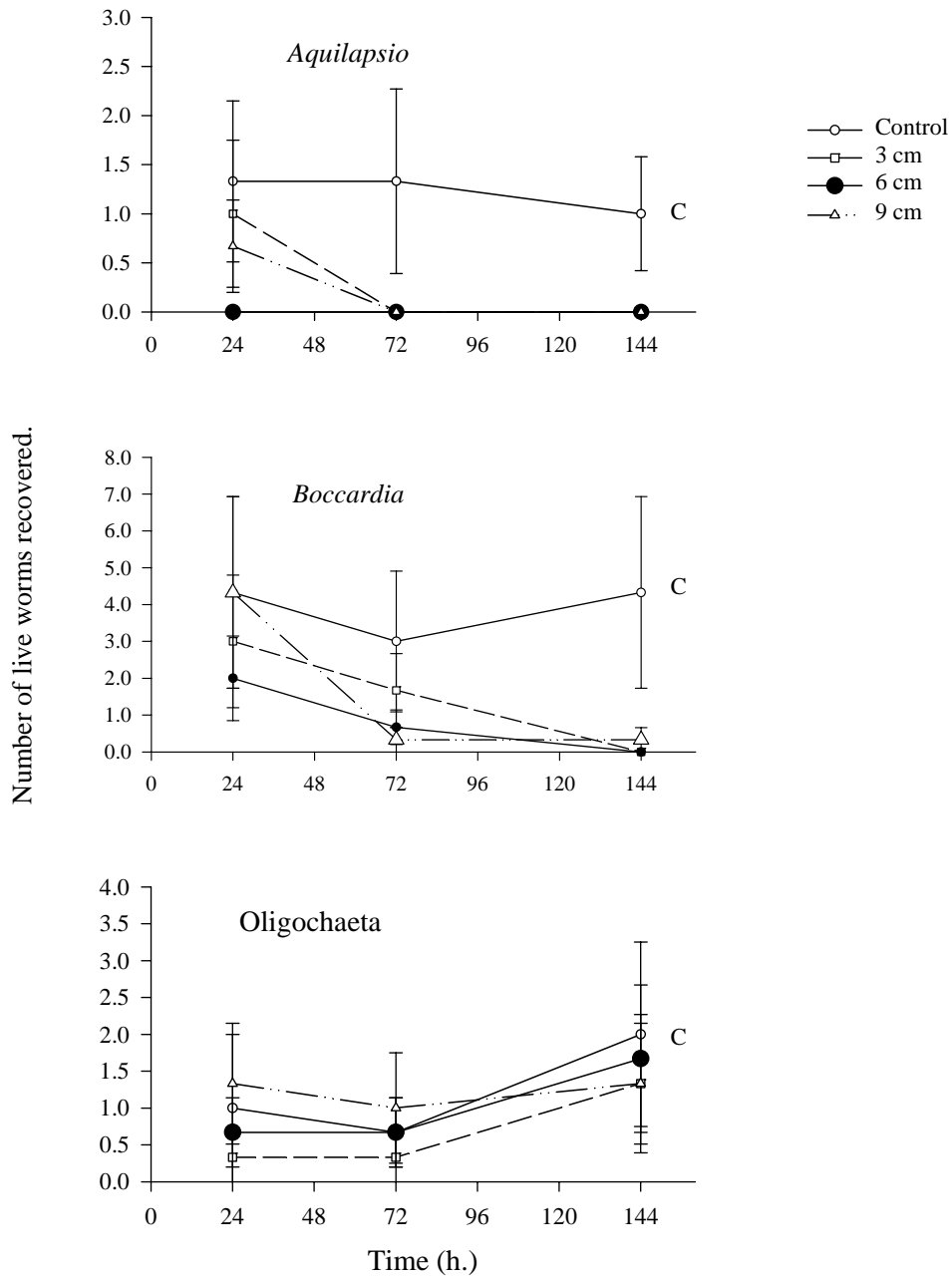
4.1.7 Other worms

Other worms were observed in the cores containing Nereidae in the experiment run with 3.0, 6.0, and 9.0 cm of clay, including the polychaetes *Aquilapso*, *Boccardia*, and a small number of Oligochaeta. Figure 7 shows that both *Aquilapso* and *Boccardia* are

present in the cores with clay after 24 h but numbers drop to zero after 72 and 144 h. This drop in numbers is more pronounced in those cores with more clay. In comparison, numbers in the control cores are relatively constant over time.

In the experiment with 0–1.5 cm clay depths there were a number of other worm taxa observed in the cores. Unfortunately these taxa were generally low and variable in numbers and did not include consistent numbers of *Boccardia*, *Aquilaspio* or *Oligochaeta*. However it is interesting to note that worms were distributed throughout the muddy sediment layer. This is in contrast to the cores with greater depths of clay (3.0, 6.0, and 9.0 cm) where no worms were found in the clay layer. The thinner clay layers may have allowed these worms to move through the clay to the surface.

Figure 7: The number of *Aquilapsio*, *Boccardia* and *Oligochaeta* recovered from cores after 24, 72 and 144 h. Each line represents the mean (\pm SD) of 3 cores from 0, 3.0, 6.0, and 9.0 cm of clay.



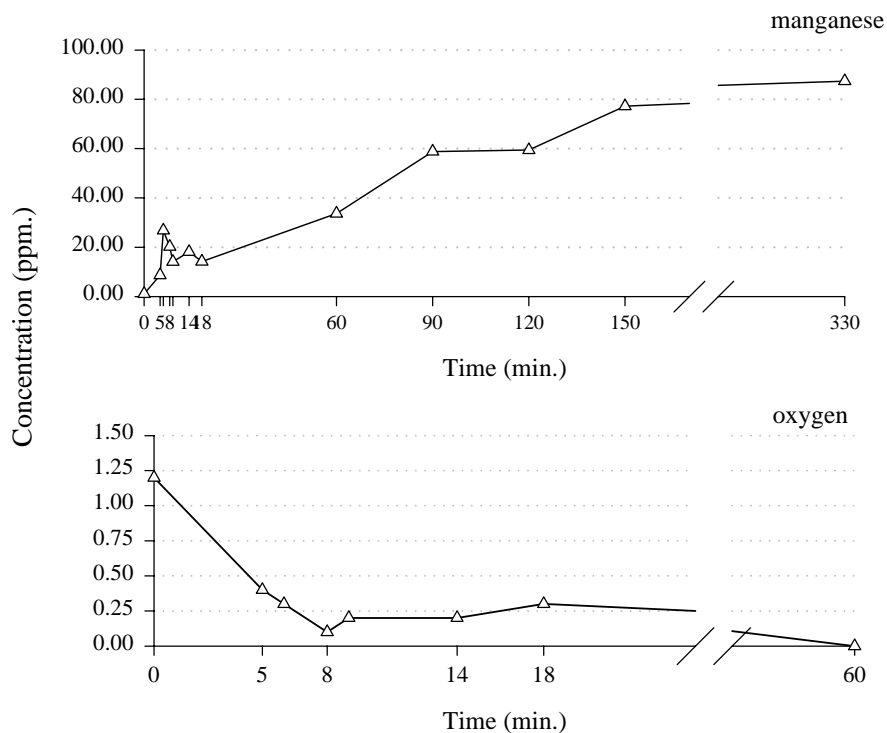
4.2 Chemical analysis

In general, the control cores contained a 2-3 mm oxic layer at the sediment surface. In cores containing Nereidae, this oxic layer was very variable due to bioturbation by the worms. Below this oxic layer, there were higher concentrations of metal ions.

In the clay treatments the oxic layer at the original sediment surface disappeared within 10 minutes following the addition of the clay, thus anoxia was rapidly induced after the deposition of clay. Within two and a half hours very high concentrations of manganese (Mn^{2+}) had developed (Fig. 8) These high manganese levels are probably produced when, in the absence of oxygen at the surface, meiofauna and bacteria switch to heterotrophic reduction of manganese oxides (MnO_2) to produce O_2 . After 144h, the surface of the muddy sediment under the clay had high levels of sulfide, Fe^{2+} and iron-sulfur ions probably also caused by heterotrophic reduction. These metal ions are potentially toxic to most animals.

The clay slurry itself was relatively oxic and contained a high percentage of porewater manganese (Mn^{2+}). This did not change over the experimental period.

Figure 8: Levels of manganese (Mn^{2+}) and oxygen (O_2) at a depth of 1 mm in the muddy Okura sediment over time, following the addition of a 3.0 cm layer of clay.



5 Discussion

All the macrofauna used in the experiments, with the exception of the Oligochaeta, were sensitive to the added deposits of clay. Lethal effects appeared to be closely linked to the size and mobility of different animals. The highly mobile snapping shrimp exhibited a relatively low rate of mortality of the seven taxa tested and easily burrowed through to the surface of the clay. Mobile but slow moving snails (*Amphibola*), varying in size from 1.0-2.0 cm, were able to burrow through clay depths up to 1.5 cm, but coped poorly in depths of 3.0 cm and greater. For *Nucula* (a less-mobile small animal) which could not move up through the clay, the difference in clay depth was less important because even in cores with 0.5 cm of clay, they were completely smothered.

As shown by the chemical conditions under the clay, anoxia was induced within the 10 first minutes after deposition of clay. Thus apart from being physically smothered by the clay the tested animals were also rapidly subject to unfavourable chemical conditions in areas where feeding normally occurs.

At the clay depths of 3.0, 6.0, and 9.0 cm the results from this experiment are consistent to those found by Norkko et al. (1999), who tested the effects of sediment depositions on 3 bivalves (*Austrovenus stutchburyi*, *Macomona liliana* and *Paphies australis*), 2 polychaetes (orbinids and glycerids) and a crab (*Helice crassa*). Table 1 below summaries both the findings of Norkko et al. (1999) and this experiment. Interesting, there is no obvious difference between the results for animals from sandy or muddy habitats.

Thus it is clear that although the test organisms used in this study are better adapted to muddy and more anoxic sediments, many are as sensitive to depositions of terrestrial clay as taxa found in more sandy sediments. Life-history characteristics, particularly mobility, emerges as the most important factor affecting the survival to depositions of clay. This is demonstrated for the burrowing shrimp in this study and for the mud crab *Helice* in the study by Norkko et al. (1999), which both readily emerged through the clay.

The resilience of Oligochaeta to the deposition of clay is potentially due to their higher tolerance to anoxia than the other taxa in the experiment. If the experiment was run for longer than 144 h a higher rate of mortality may have been observed.

Table 2: Taxa from both sandy and muddy habitats. Ranks based on relative performance in the laboratory experiment by Norkko et al. (1999) and this experiment. Relative mobility is a score from 1 to 5, where 5= mobile and 1= sedentary. Effect ranks are for the overall effect of clay depth and time on animals. This ranges from 1 to 5, where 5= no effect. The score for overall sensitivity is the sum of scores for relative mobility, depth and time.

Taxa	Preferred habitat	Functional group	Relative mobility	Effect		Overall Severity
				Depth	Time	
<i>Macomona</i>	s	sd	4	3	2	9
<i>Austrovenus</i>	sm	ss	3	2	4	9
<i>Paphies</i>	s	ss	5	3	5	13
<i>Helice</i>	m	sd/p	5	5	5	15
<i>Glycerid</i>	sm	p	4	5	3	12
<i>Orbinia</i>	sm	d	3	2	2	7
<i>Amphibola</i>	m	sd	3	2	2	7
<i>Nereidae</i>	sm	sd/p	3	4	2	9
<i>Alpheus</i>	ms	sd/p	5	5	4	14
<i>Nucula</i>	ms	sd	2	3	3	8
<i>Aquiaspio</i>	sm	sd/ss	1	4	1	6
<i>Boccardia</i>	sm	sd/ss	1	4	2	7
<i>Heteromastus</i>	sm	d	1	5	5	11
Oligochaeta	sm	d	2	5	5	12

s=sand
sm= sand then mud
ms= mud then sand
m= mud
sd= surface deposit feeder
ss= suspension feeder
p= predator/scavenger
d= sub surface deposit feeder.

The silt content and fluidity of the sediment is an important parameter which may change the ability of the fauna to regain their position in the upper sediment layers after burial. High silt content and fluidity may prevent the animals from getting resistance in the sediment for climbing. Both Glude (1954) and Maurer et al. (1986) found that high silt content of the sediment increased mortality of bivalves and gastropods. This effect was attributed to failure in climbing up through the sediments. Also Chandrasekara & Frid (1998) showed that high water content (similar as in this study) of the sediment deposits significantly impaired the ability of gastropod taxa to bury up through the sediment. Thus our results are consistent with those previously reported in the literature.

Because of the restricted capability of animals to migrate through the depositions of clay, the length of time the animals are smothered emerges as a key factor determining the ecological effects of sediment depositions. As shown in this study and by Norkko et al. (1999) some taxa survive up to 6 days of burial by "shutting down" and utilising anaerobic metabolic pathways. In the upper reaches of a small estuary such as Okura hydrodynamic forcing through wave action and tidal currents is much

reduced compared to areas closer to the entrance. The layer of clay would thus take much longer to be broken up and get washed away. Also the biogeochemical evidence produced in this experiment indicates that it takes only minutes for the surface oxic layer of the muddy sediment to become anoxic once covered by the clay. Evidence also showed that even the smallest amount of clay will cause the same effects as the largest deposit. Therefore a critical component in determining the mortality of macroinvertebrates in the upper reaches of an estuary would be the time that an area of mudflat was covered by clay.

In this situation, the role of bioturbators such as the large bivalves, *Macomona*, *Austrovenus* and crabs like *Helice crassa* and burrowing shrimp, *Alpheus*, would be more important in breaking up the clays and mixing the sediment and the clay layer together, than in areas where the sediments are more mobile.

6 Conclusions and Recommendations

From these results we can conclude that the deposition of clay, greater than 0.5 cm thick onto muddy sediments like those observed in the upper reaches of the Okura estuary will have a negative effect on small, less mobile macrofauna. After 6 days these animals are showing signs of being highly stressed. Thicker clay layers will affect an increasing number of animals with layers greater than 3.0 cm affecting most animals. How lethal these effects are is dependent on both the time and depth of coverage.

Our chemical analysis shows rapid onset of anoxia within the sediments indicating that quite thin layers of sediment could have significant ecological effects if they are not resuspended and transported away by tidal flows or waves.

These experiments have enabled us to make conclusions about the short term effects of a sudden deposition of clay on muddy sediments commonly found in the upper reaches of the Okura estuary. It is important to bear in mind that these are acute and short-term laboratory experiments enabling us to say something about short-term effects. Following a sudden deposition of clay in an area like the upper Okura, ongoing monitoring in the field is needed to determine the long term effects.

7 References

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