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**Responses of subtidal benthos of the Strait of Georgia,
British Columbia, Canada to ambient sediment conditions
and natural and anthropogenic depositions**

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Abstract

Patterns in infaunal biota in the Strait of Georgia are explored relative to water depth, substrate type, organic content of sediments and sedimentation characteristics. The analyses are based on geographically-diverse grab and core data collected over a 19-year period.

Infaunal abundance and biomass were not predictable by sediment particle size, organic content or water depth. While organic flux was a reasonable predictor of biotic factors, quality of organic material, relative proportions of organic and inorganic input, and source of inputs were also important in this regard. Areas with high accumulation of sediment and high organic flux rates from terrestrial (riverine) sources supported the highest macro-infaunal abundance and biomass found to date in the Strait of Georgia, and were dominated by bivalves. Polychaetes dominated in low organic deposition conditions, and where anthropogenic organic deposition was high. However, biota were severely impoverished in sediments with high organic content from marine deposition, due to low fluxes and poor quality of organic material. Taxa number was related to percent total nitrogen and to the ratio of organic/inorganic flux, both in background conditions and where there was labile organic enrichment. Faunal communities from the Fraser River delta, which experiences considerable bottom-transported riverine material, were very different in composition from those that proliferate in habitats with high deposition and organic flux from the water column.

Key words: marine benthos, sedimentation, Strait of Georgia, infaunal biomass

1.0 Introduction

In the Pacific northwest, the two most consistently important physical factors affecting marine benthic biota appear to be substrate type and water depth (Striplin, 1996; Llansó et al., 1998; Striplin and Weston, 1999). In general, as water depth increases, biotic communities in coastal marine areas experience reduced organic input, lower currents (and potentially lower oxygen), and more stable temperature, salinity and hydrographic conditions. Globally, benthic invertebrate production and production/biomass ratios tend to decrease with increasing depth (Jumars and Banse, 1989; Cusson and Bourget, 2005). Ellis (1971) found, in his early review of benthic fauna from the Strait of Georgia, that biomass was considerably higher in shallow areas than in deeper stations within the Strait and in the surrounding fjords and channels. On open continental shelves, substrates tend to get finer with water depth and organic flux from coastal sources usually (but not always) decreases (Vinogradov and Tseitlin 1983; Shirayama 1984; Vanaverbeke et al., 1997). However, this generalization can be affected by strong topographic and seasonal drivers (Aller et al., 2002).

For British Columbia, Canada, which has a diverse and geographically extensive coastline, topography and currents vary widely, such that depth, substrate type and organic loading are spatially and temporally variable and complex. In the inland sea of the Strait of Georgia, there is strong estuarine circulation related to seasonal input of particulates, freshwater and organic carbon (OC) from the Fraser River (Johannessen et al., 2003; Hill et al., in press) and other lesser freshwater sources. Over the past century, discharges from agriculture, industry and urbanized regions in the southern Strait of Georgia have further complicated natural deposition.

The main objective of this paper is to contribute to the understanding of natural and anthropogenic factors that affect benthic biomass and productivity in the Strait of Georgia. Herein, we examine recent general patterns of benthic macro-invertebrate fauna in the Strait of Georgia and surrounding fjords seeking relationships with depth, substrate type and organic content of sediments. These biotic patterns are then compared with organic and inorganic flux to the sediments as well as the quality and composition of sediments.

2.0 Methods

2.1 Data sources and comparisons

The biotic database used herein includes abundance data for benthic invertebrate species from 607 grab samples collected between 1988 and 2006, from areas of the Strait of Georgia and surrounding fjords which are remote from anthropogenic discharges (referred to as “background” areas). The database also includes 347 biotic samples from near-field areas of current anthropogenic discharges, where biotic changes related to the discharge have been identified (Table 1). Data from these samples will be referred to herein as “anthropogenic”, to facilitate comparisons with biotic distributions from background areas of the Strait. We recognize that this distinction is somewhat artificial, as contamination from human activities has spread widely throughout the Strait during at least the past century (Macdonald et al., 1991; Johannessen et al., 2005a,b). Anthropogenic input areas for which these same data are available (Fig. 1) include: Iona Island wastewater outfall (off the North Arm of the Fraser River); Lions Gate wastewater outfall (in Burrard Inlet); Macaulay Point wastewater outfall (Juan de Fuca Strait). Although the Macaulay Point outfall is not in the Strait of Georgia (Fig. 1), vigorous currents, high mixing, sediment re-suspension and lack of confounding inputs provides an alternative habitat to

examine the effects of sediment conditions on biota in an organically enriched habitat; five pulp and paper mills¹; and Britannia Beach mine in Howe Sound. Anthropogenic data were overlaid on the background data plots to examine biotic changes relative to anthropogenic inputs.

The data used may be found in various technical reports and unpublished sources listed in Table 1; general locations of sampling programs are shown in Fig. 1. All biotic samples were collected using 0.1m² surface area grab (Smith-McIntyre or Van Veen) with stated minimum volume requirements for samples of at least 2/3 capacity. All samples were processed using a 1 mm sieve, with full taxonomic identification to species wherever possible. Detailed sampling protocols and quality control information are described in the original reports. Although quality control likely varied among studies, the data were sufficiently uniform in approach and method of collection to provide assessment of general trends.

Data for sediment total organic carbon (%TOC) were available for most samples, whereas data for percentage of total nitrogen (%TN) were available for a limited number of samples in the historical database.

For the analyses presented here, biological data from the sources indicated in Table 1 were assigned consistent taxonomic codes and entered into a master database, along with ancillary sediment measurements of geophysical properties and contaminant concentrations. Data on hydrozoans and bryozoans, which were not included consistently in all studies, were not entered into the database. Meiofauna were not considered to be representatively sampled with a 0.1 mm

¹ Pulp mills included were Catalyst Paper Corporation (Powell River and Crofton), Howe Sound Pulp and Paper Ltd. (Port Mellon), Western Pulp Ltd. (Squamish), Pope and Talbot Ltd. Harmac (Nanaimo),

mesh screen (nematodes, harpacticoid copepods) and, therefore, were not entered into the database.

Summary assessment measures for infaunal benthos typically used in Pacific northwest jurisdictions include taxa number and faunal abundance (Washington State Sediment Management Standards: www.ecy.wa.gov/programs/tcp/smu/sediment.html; Striplin, 1996; Stiplin and Weston, 1999; GVRD, 2004). In addition, Burd (2006) found that bivalves, sedentariate polychaetes, errantiate polychaetes and crustaceans are typically found in most background marine sediments from coastal British Columbia. The abundance of these ubiquitous faunal groups, along with total abundance and taxa number from the historical grab sample were plotted against sediment depth, silt+clay (% fines) and, where available, sediment %TOC and %TN for samples from background locations, with data from samples affected by anthropogenic inputs overlaid for comparison.

The data include taxa abundance and taxa-specific biomass from triplicate grab samples at nine locations, as part of a dedicated Ambient Monitoring Program (AMP) in the Strait of Georgia (Fig. 2, Table 2, Wright et al., 2008). Methods for biological sampling and processing are described by McPherson et al. (2007a, b). Eight of the AMP locations were from background areas of the Strait; however, one of the AMP sample locations was placed near the largest municipal outfall in the Strait to determine whether there are detectable differences in organic fluxes and biological composition at this location relative to surrounding areas. Surface sediment measurements of total carbon, total organic carbon (%TOC), total inorganic carbon

(%TIC), total nitrogen (%TN), organic carbon (OC) and inorganic carbon (IC) fluxes and stable isotopes of carbon and nitrogen ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) were measured from nine cores from the AMP.

With the exception of seasonal, or intermittent, anoxic events in two peripheral fjords (Saanich Inlet and Howe Sound), bottom waters of the Strait of Georgia are always oxygenated ($>2.5 \text{ mL}\cdot\text{L}^{-1}$) (Masson, 2002) and support an active benthic community which mixes the surface sediments through bio-turbation (Johannessen et al., 2005b). Sedimentation, and mixing rates in the sediment cores were determined using excess ^{210}Pb profiles in sediments together with advective-diffusive models (Johannessen et al., 2005b). The depth of the surface mixed layer in each core was determined from the ^{210}Pb profile. Organic carbon was calculated as the difference between total carbon and carbonate carbon, based on the method of Calvert et al. (1995). The incident flux of OC, the %OC buried, and the %OC oxidized were estimated from the ^{210}Pb profiles of %OC measured in the sediment cores (for methods, see Johannessen et al., 2008).

To supplement data from the AMP cores, historical core data for sedimentation rate and organic flux to sediments calculated in the same manner (data sources in Table 2) were included in plots of geographic distribution of sedimentation characteristics using variable-weighted VG gridding in Ocean Data View (Schlitzer, 2006). Similar plots were made for sediment percent fines as well as several biotic factors. Note that the extrapolated values are not valid near shore. The historical data were not used for any further calculations (see below).

2.2 Data Analyses

Gaps in the physical/chemical data from the historical database resulting from differences in the suite of sediment variables measured between individual studies, prevented the application of multi-factor comparisons such as multiple regression, ordination or clustering methods.

However, the AMP data (nine cores and grab sample locations) were examined in greater detail than the historical data, to seek effects of sediment factors and sediment flux trends on biota. In addition to the biotic factors examined for the historical data, total faunal biomass and abundance of several other common biotic groups were analysed (gastropods, ophiuroids and holothuroids) for the AMP data. Although these additional faunal groups are patchy in distribution, they can contribute considerably to faunal biomass, and their presence/abundance may help explain biomass trends.

Relationships between biotic factors and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ composition, sedimentation rates and organic flux to sediments were explored initially for the AMP grab/core data using Pearson correlations. In addition to the measured sediment factors, and the modeled sediment flux factors, a “weighted” OC flux, which takes into account the relative lability of organic material, was calculated to correlate with biotic variables. With a consistent organic source, elevations in $\delta^{15}\text{N}$ have been shown to indicate increased trophic reworking in the water column due to preferential use of the lighter isotope (c.f. Burd et al., 2002) and thus, are likely to indicate decreased lability of organic material. Therefore, the weighted organic matter factor used to compare with biotic factors was OC flux divided by $\delta^{15}\text{N}$. Although weighting using $\delta^{15}\text{N}$ is based on a simplistic assumption for the Strait of Georgia, and may be confounded by the

relative proportion of terrestrial versus marine organic input (Johannessen et al., 2005b), it does reflect the observed differences in values for the Iona outfall deposits (very low $\delta^{15}\text{N}$), the Fraser River deposits (moderate $\delta^{15}\text{N}$ from agricultural sediment input), and higher $\delta^{15}\text{N}$ from the central deep basin (cores GVRD-1,10; Fig. 2), which is much more distant from major riverine deposits.

No hypotheses were tested by correlation; rather, this approach helps to identify potential relationships which may be explored further. Where notable correlations were evident, or non-linear patterns suspected from data distribution plots, non-linear regression analyses (Zar, 1984 – exponential models) were used to examine variability in biotic versus sediment or sediment flux factors.

3.0 Results

Historical samples, which ranged in substrate type from 0 to 100% fines (=silt+clay), were drawn from depths ranging from 9 to 700 m. The main basin of the Strait is uniformly silty from the south end to the middle of the Strait (around Texada Island), north of which the basin becomes shallower and more mixed in substrate type, with extensive erosional sand and gravel beds along the coastline of eastern Vancouver Island (Burd et al., in press). Samples from the deep basins of the mainland fjords (Jervis, Toba and Bute Inlets) have high percent fines (Burd and Brinkhurst, 1992). The near-shore areas of the fjords tend to have more mixed sand/silt near river deltas. Near-shore substrate detail can be found in the Provincial Physical Shoreline map for British Columbia, (Howes et al., 1994) at URL: <http://maps3.gov.bc.ca/imf406>.

Historical data showed that faunal abundance and taxa number increased with depth subtidally, peaked between 60 and 80 m, and then declined below 100 m in all samples (Fig.3). This trend was most obvious in bivalves, and less so in polychaetes and crustaceans.

In the Strait of Georgia, sediment grain size appears to have limited influence on the general benthic faunal indicators used herein (Fig. 4), even though it is expected to affect species distributions. In background samples, total abundance was highest in mixed sediments (60-80% silt/clay), and slightly lower at both lower and higher percent fines (Fig. 4). However, samples taken near the Macaulay outfall showed very high abundance in samples with low percent fines, particularly with respect to polychaetes and crustaceans. Other biotic factors showed no discernible trend with % fines (Figs. 4a,b). Infaunal bivalves tended to be rare where sediment fines were <20%, as in areas disturbed by current anthropogenic inputs.

In background samples, faunal abundance was highest where %TOC was 1-1.5 (Fig. 5a). However, faunal abundance was moderate to high at much higher %TOC levels in some samples near Macaulay outfall, as well as near the pulp and paper discharges (including some samples used as reference sites during a past pulp mill monitoring program). Taxa numbers declined with increasing %TOC in background and sewage outfall samples (Fig. 5a), but were unpredictable relative to %TOC near pulp mills. Lowest taxa numbers were found in Britannia near-shore sediments, with no discernible relationship to %TOC. Notably, taxa numbers were not unusually low at any location, even where %TOC was high. Bivalves tended to be in low abundance in most of the pulp and paper samples and all of the samples taken near the historical Britannia mine, and, like total abundance, bivalve abundance peaked between 1% and 2% TOC (Fig. 5a).

Crustaceans, errantiate and sedentariate polychaete abundance did not show any clear relationship with %TOC (Fig. 5b), except for a slight decline in crustacean abundance with increasing %TOC in background samples. Some samples from near the Macaulay outfall with high %TOC values showed enrichment by opportunistic polychaetes, such as *Capitella capitata* complex.

Sediment %TN provides a simple measure of organic composition and quality. Relatively high nitrogen content implies marine or aquatic food web sources containing protein, whereas low nitrogen content implies terrigenous organic matter (woody or humic material; eg. Webster and Benfield, 1986). Total abundance, bivalve abundance and taxa number tended to decrease with increasing %TN (Fig. 6a), although more variable results for bivalves may have been confounded by the dramatic decline in abundance below 150 m depth, while %TN was higher in deep, background samples. The declining trend with increasing %TN was less clear for crustaceans and not evident for either polychaete group (Fig. 6b) or for samples collected near pulp mills.

Sediment accumulation rates (Fig. 7a) were highest immediately off the mouth of the south arm of the Fraser River (GVRD-4). Sedimentation rate was too high to measure accurately in this shallow core based on Pb^{210} , and was therefore estimated (see Table 3) based on maximum values in other cores and measurements from the literature. Previous work has shown sedimentation rates near the Fraser delta in the range of 3 -13 cm/year (Evoy et al., 1993; Hart et al., 1998). They were also relatively high in the southern deep basin of the Strait, and tended to decline with distance northward. The pattern for organic flux to sediments, based on fewer data

points (Fig. 7b), was similar to that for sediment accumulation, indicating that the material contributed by the Fraser River is an important source of both organic and inorganic matter to the Strait.

Faunal abundance was highest overall along the bank off the Fraser River discharge, and particularly near the south arm (Fig. 8a). Abundance was moderately high just outside Saanich Inlet in the Satellite Channel area, in the southern-most portion of the main basin of the Strait, and off the south end of Victoria in Juan de Fuca Strait. It was lowest in the deep, mainland fjords along the western margin of the Strait, and in all sample locations in the northern half of the Strait. Although data are limited, faunal abundance appears also to be high within the island archipelago at the north end of the Strait. Bivalve abundance showed a similar pattern to overall abundance (Fig. 8b), with maximum values off the bank and slope spanning the Fraser River discharges. Although taxa numbers (Fig. 9) were high off the south arm of the Fraser River, they were also high in several widely separated areas at the northern and southern ends of the Strait. Taxa numbers were low in the central and northern portions of the main basin.

A general understanding of the sources and quality of organic matter in sediments may often be gained by examining the distributions of %TOC and %TN, and their stable isotopic compositions ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) (e.g. Johannessen et al., 2005b). An examination of these components for the seven sediment cores from the AMP shows that the northernmost core (GVRD-1) is distinct from all other cores (Fig. 10, Table 3) in having high sediment %TOC and %TN and high $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, marking it as the core most influenced by marine-derived organic matter. In contrast, low %TOC and %TN values throughout core GVRD-3, near the Iona outfall and for the station off

the south arm of the Fraser River (GVRD-4), indicate strong terrigenous input due to a large supply of riverine inorganic material. Recent Iona outfall deposits (after commissioning of the deep-sea outfall in 1989) have a unique, low $\delta^{15}\text{N}$ signature compared with pre-outfall deposits and other core locations in the Strait (Fig. 10) indicating a distinct source of organic matter at that site. The isotopic composition of the sedimentary organic matter suggests that the proportion of terrigenous organic matter is greatest near the Fraser River and decreases northward (see Johannessen et al. (2005b) for a discussion of the application of stable C and N isotopes to discriminate sources of organic matter).

Sediment accumulation rate, OC flux, inorganic flux and buried OC flux were highly inter-correlated ($r^2 = 0.98$ not shown). These four factors did not always correlate consistently with a given biotic factor, but consistent patterns are notable. For example, biomass, gastropod and crustacean abundance correlated positively with all four of the aforementioned factors. In contrast, the ratio of polychaete abundance to total abundance correlated negatively with the four sediment factors, as well as with oxidized OC flux.

Total abundance, biomass, ophiuroid, bivalve, gastropod and sedentariate polychaete abundance were moderately to highly positively correlated with total flux, OC flux, OC flux weighted by $\delta^{15}\text{N}$, inorganic and buried OC fluxes. Oxidized OC flux, which would be expected to be a good indicator of biological activity in sediments, was not strongly positively correlated with any biological factor.

The percent carbonate in surface sediments showed moderate to strong positive correlation with a range of biotic factors, including taxa number, total abundance, abundance of ophiuroids, bivalves, errantiate and sedentariate polychaetes. However, the proportion of both types of polychaetes showed a low negative correlation with %carbonate. A very similar pattern of positive and negative correlations was evident between these biotic factors and organic flux weighted by $\delta^{15}\text{N}$. Percent bivalve abundance was strongly negatively correlated with $\delta^{15}\text{N}$, and $\delta^{13}\text{C}$.

The number of taxa was most strongly negatively correlated with organic/inorganic flux ratio, %TN and %TOC. A plot of taxa number vs. organic/inorganic flux showed a negative exponential relationship ($r^2 = 0.87$, Fig. 11). The best fit line for this function was superimposed on the scatterplot for taxa number versus %TN for combined historical and AMP data from all background and anthropogenic sites (Fig. 11), which also showed an exponential correlation ($r^2=0.76$). Both of these regressions were highly significant ($P<0.0001$). The two functions show very similar shapes and slopes. Only the data for samples near pulp mills showed unusual deviations from the primary trend.

The highest faunal biomass was found in cores GVRD-4 and -6, followed by core GVRD-5 (Fig. 12). Total biomass was positively exponentially correlated with sediment accumulation rate (Table 4), OC flux, inorganic flux, and buried OC flux. The buried OC flux explained 84% of variance in faunal biomass (Fig. 12). Biotic factors did not show any correlation with AVS concentration (Table 4), and do not show any relationship to biotic factors in the historical database (not shown).

4.0 Discussion

4.1 Geographic distribution of sedimentation and biota

The highest sediment accumulation rates and organic fluxes occur along the eastern margin of the Strait, off the Fraser River, with the nearby station GVRD-4 having the highest estimated fluxes for this study (Hill et al., in press). Sandy silt from the Fraser River is transported outward from the delta along the bottom northward and downslope (Pharo and Barnes, 1976; Evoy et al., 1993; Hart et al., 1998; Hodgins and Hodgins, 2000; http://gsc.nrcan.gc.ca/marine/gbgi/proj_surf_e.php, 2006; Hill et al., in press). The organic and inorganic sediments from the Fraser River dominate the input to sediments near the Fraser delta (Hodgins and Hodgins, 2000; Hill et al., in press). The Iona Island wastewater outfall, which is the largest volume marine sewage discharge in British Columbia ($145 \times 10^6 \text{ m}^3/\text{yr}$ water), is located about 10 km N of the south arm along the Fraser River foreshore, and discharges through diffusers at 60-90 m depth (Fig. 1). Model results (Hodgins and Hodgins, 2000) indicate that the maximum particle deposition from the Iona outfall ($\sim 0.3 \text{ gcm}^{-2}\text{yr}^{-1}$) occurs within the first km north of the outfall. The sedimentation rate estimated from a core collected at that location (GVRD-3) is $1.34 \text{ gcm}^{-2}\text{yr}^{-1}$. Therefore, about 25% of the total sedimentation just north of the Iona outfall could be accounted for by municipal outfall discharge, with the other 75% coming from the Fraser River. This estimate is relatively close to that noted by Macdonald et al. (in press), using Zn/Cd ratios in effluent and sediments. The suspended particles from the outfall contain about 30% TOC (S. Bertold, Metro Vancouver, pers. comm.). Therefore, with the 75% dilution from the Fraser River particulates, which contain <1% TOC (Johannessen et al., 2003),

the sediment %TOC just north of the outfall should be about 7-8%. In fact, the sediments near the outfall are within background levels for %TOC content (<1.5%). There are several possible explanations for the discrepancy; 1) the model overestimates sedimentation to the bottom from the outfall; 2) most of the sedimenting organic material is rapidly broken down within sediments (supported by high oxidation rates in the current study), or; 3) most of the organic material from the outfall does not reach bottom due to biogenic uptake or degradation in the water column.

Faunal abundance and biomass were highest in the Fraser River frontal area, suggesting that these are highly productive sediments. Bivalves dominated the fauna in this area (40-60% of abundance and biomass - Fig. 8b and Burd, 2003a; McPherson et al., 2007a) more than anywhere else in the Strait. Other authors have noted dominance by infaunal bivalves in marine sediments subject to terrigenous inflow in Arctic and subarctic coastal areas (Thorson, 1957; Wlodarska-Kowalczyk and Pearson, 2004; Wlodarska-Kowalczyk et al., 2007 and references therein). Wlodarska-Kowalczyk (2007) and Wlodarska-Kowalczyk et al. (2004, 2005, 2007) suggested that sediment stability played a major role in structuring faunal type and productivity, with the consequence that the dominant benthic organisms were bivalves in intermediate deposition areas, opportunistic (recolonizing) polychaetes in very high deposition areas (up to 36.5 g/cm²/a) with slope instability, and a variety of primarily tube-building polychaetes in low deposition, deep areas. They found that faunal biomass was highest in areas of intermediate deposition, falling off in both the lower and higher deposition areas. Results from the current study support this general pattern. For example, polychaetes tended to be the dominant fauna in areas of the Strait where sedimentation and organic flux were low. Although unstable areas with extremely high deposition were not sampled in this study, the location with the highest

deposition (GVRD-4, near the south arm of the Fraser River) has shown a recent increase in dominance by small, rapidly recolonizing polychaetes where bivalves were much more dominant previously (McPherson et al., 2007a). This location could have experienced an increase in particulate deposition from the river in recent years.

In the southern Strait (core GVRD 6 – 187m deep), fine sand and silt suggest deposition from the river either directly or through resuspension, and/or erosion of material from the southern Gulf Islands via energetic tidal mixing and currents that transport material northward via Haro Strait (Masson and Cummins, 2004; Johannessen et al., 2006). Particulate organic matter, enhanced bacterioplankton production (Albright, 1983) and inorganic particles in the Fraser River plume contribute to the high flux. Biotic abundance and biomass were relatively high at station GVRD-6. The major difference in biota between the delta/slope area and the deeper, southern basin of the Strait, was that the latter had lower overall abundance, a lower proportion of bivalves, and greater dominance by crustaceans and holothurians. However, total biomass in the two areas was similar.

Sedimentation, organic flux, infaunal abundance, biomass and taxa number were all lowest in the basin north of Texada Island (GVRD-1, GVRD-10). This is not surprising, since evidence from sediment trap (Johannessen et al., 2005b) and multi-beam (Hill et al., this issue) studies indicate a minimal influence of Fraser River particles in the north-central and northern Strait. Long-term monitoring shows that the total water column primary production is greater in the northern Strait than it is in the southern basin (D. Masson, Fisheries and Oceans Canada, personal communication, 2008), and particles that sink in this area have a higher organic content than

elsewhere in the Strait (Johannessen et al., 2006). The flux of these organic-rich particles seems to peak in late spring, after the main spring bloom. Consequently, the organic matter in the sediments of the northern Strait is mostly marine (Johannessen et al., 2005b), along with some terrigenous organic matter added by pulp mills within the northern half of the Strait (Macdonald et al., 1991).

Sedimentation rates for the inlets and fjords seem to be relatively low compared with the Fraser River delta/slope area, based on historical core data for Burrard Inlet and Howe Sound (Table 2). In outer Burrard Inlet, sediment accumulation rates are considerably lower than along the Fraser River delta/slope, whereas faunal abundance and biomass are only moderately lower (McPherson et al., 2007b). Bivalves predominate in outer Burrard Inlet, as they do along the Fraser River foreshore (Je et al., 2003; McPherson et al., 2007b), suggesting moderate deposition rates. Carbon/nitrogen ratios and stable isotopes suggest that sedimenting material in the outer Burrard Inlet comes primarily from the Fraser River (Boyd et al., 1997), however numerous types of anthropogenic discharge contribute unknown quantities of particulate material as well. High flocculent content in the water column observed near the First Narrows bridge (CORI, 2002) suggests that the strong currents re-suspend material from the bottom, reducing the predictability of biotic abundance and biomass based on core-derived flux rates (McPherson et al., 2007b).

The sediment accumulation rate is lower in the main basin of Howe Sound than in outer Burrard Inlet (Johannessen et al., 2003), as is faunal abundance. However, confounding factors in Howe Sound undoubtedly affect biotic conditions. These include discharges from two pulp mills, acid mine drainage that continues to leak from an abandoned copper mine (Britannia), and

intermittent stagnation in the deep basin water behind the sill (Levings et al., 1983; Stucchi, 2006).

Sediments in the deep basin of Jervis Inlet (Burd and Brinkhurst, 1992) are composed of uniformly fine silt (~98%), similar to those in the deepest deposition areas of the main basin of the Strait. This suggests that particulate flux to these sediments is low. Total faunal abundance was lower in samples from the deep basin of Jervis Inlet than in Howe Sound or outer Burrard Inlet.

Aside from a few measurements from just north of Saanich Inlet (Burd, et al., 2000; Burd and Glaholt, 2000; Seacology, 2001; Glaholt et al. 2002), and from several pulp mill areas, there are few biological or core data available from the near-shore areas along the western margin of the Strait, so fluxes cannot be compared for this region. In Saanich Inlet, historical organic flux data to sediments at the CEPEX site just inside the sill (Whitney and Wong, 1984) suggest rates intermediate between those found at the Iona outfall station (GVRD-3) and at the station outside Burrard Inlet (GVRD-2). However, bottom water hypoxia is the most important factor structuring benthic communities in Saanich Inlet (Tunncliffe 1981; Burd and Brinkhurst, 1984).

4.2 Predictability of biotic patterns from ambient and sedimentation conditions

Percent fines was not a major factor structuring the biotic indicators measured during this study (see also Levin and Gage, 1998), although it is expected to have a profound effect on community composition and balance of feeding types (Bernard, 1978; Levin and Gage, 1998). The current study shows that biotic declines tended to occur below 100 m depth, and even more dramatically

below 300 m depth. This decline with depth, which has also been observed in other high-latitude seas from the continental margin (about 200 m) to abyssal depths (3000 m – Levin and Gage, 1998; Wlodarska-Kowalczyk et al., 2004), parallels the observed decline in organic input with depth (Suess, 1980; Vinogradov and Tseitlin, 1983; Shirayama, 1984; Bishop, 1989; Vanaverbeke et al., 1997).

The data from the current study clearly illustrate that sediment organic content is a poor predictor of benthic macro-infaunal abundance and biomass in the Strait of Georgia. Hyland et al. (2005) suggested that infauna increase in abundance and taxa number as organic content increases, up to a threshold, beyond which they decline (as per Pearson and Rosenberg, 1978). This pattern can be seen near the Macaulay Point outfall south of Greater Victoria (Fig. 1) (Burd, 2003b). However, organic enrichment gradients cannot always be identified by sediment organic content. For example, organic loading from the Iona outfall in the Strait of Georgia is swamped by a large, primarily inorganic deposition from the Fraser River (Hodgins and Hodgins, 2000; Yunker and Macdonald, 2003; McPherson et al., 2007a), so that sediment organic content remains within background ranges along the delta. However, there is evidence of elevated sulphides in sediments and enrichment-related faunal changes near the outfall (Burd, 2003a; McPherson et al., 2007a).

A further example of the unexpected relationship between sediment organic matter and biotic conditions in the Strait of Georgia was evident in the samples taken from Texada Island northward. Unusually high sediment OC, nitrogen and $\delta^{15}\text{N}$ in the cores (GVRD-1 and 10), and

notably impoverished biota suggest that sedimenting marine organic material is recalcitrant in that region of the Strait and contains little of nutritional value by the time it reaches the bottom.

Organic flux to sediments is a much better indicator of biotic abundance and biomass than organic content of sediments. Similarly, Rowe et al. (1991) pointed out that POC flux to sediments was a much better estimator of infaunal biomass in the western North Atlantic than sediment detrital organic content, and Grebmeier et al. (1988) showed benthic infaunal biomass to be coupled with flux of organic matter to the seabed in the northern Bering and Chukchi Seas. Johnson et al. (2007) also showed that modeled vertical POC flux from surface satellite color imagery accounted for about 2/3 of the variance in benthic standing stock of macrobenthos in the western North Atlantic.

The quality of organic matter, including contaminant content, in structuring marine infaunal growth and production has not been extensively studied but appears to an important modifier of the aforementioned POC/biotic relationships (Gunnarsson et al., 1999; Aller et al., 2002; Danovaro, 2003). A modified measure of organic flux, which took into account the relative age and lability of organic material, was a better predictor of many biotic factors than unweighted organic flux (Table 4). However, this was not true for total biomass, because the station just north of the Iona outfall skewed the relationship. Despite relatively high sedimentation rates and organic flux at this location (GVRD -3), biomass was low, due to the loss of ophiuroids and the reduction in bivalve abundance. Bivalve abundance is thought to be relatively low near the outfall because of sulphide toxicity from the organic enrichment of sediments (Burd, 2003a; McPherson et al., 2007a; GVRD, 2004). A regression of total biomass on $\log_{10}$ weighted organic

flux, calculated without the outfall station, explains 82% (r^2) of the variance in biomass. In the Strait of Georgia, this suggests that infaunal biomass can be well predicted by flux and quality of organic matter to sediments under background conditions of sedimentation, but that sediment toxicity may override the relationship in areas of anthropogenic inputs of organic matter.

In the Strait of Georgia, river-borne deposits mixed with marine flux appear to provide a more productive substrate for infauna than do marine deposits alone. Many of the abundance factors measured in this study are related to total flux as well as to % carbonates. A high concentration of carbonate in sediments usually indicates river-borne sediments, although over the small scale of the central Strait of Georgia, the carbonate distribution is patchy (Gordon, 1997), so that interpretation is not clear in this case.

Taxa number was poorly predicted by organic flux and quality. Taxa numbers in background conditions and near sewage outfalls were strongly negatively correlated with %TOC, %TN and the ratio of OC to inorganic flux to sediments (Table 4). These sediment factors were also strongly positively inter-correlated. This is not surprising, since the diversity of benthic marine faunal types is theoretically related to the diversity of substrate habitats and habitat stability within a given area (Gray et al., 2002). Based on results from extensive trawl surveys in the Strait of Georgia, Bernard (1978) suggested that the more consistently fine substrates (without terrigenous debris, shell hash, or a variety of particle sizes) had fewer habitat niches available. Therefore, %TN and relative organic/inorganic composition of sediments appear to be useful surrogates for measuring habitat heterogeneity, and thus predicting taxa number.

However, taxa number did not show any pattern with sediment organic content near pulp mills. Focused studies outside the government monitoring programs near several of the pulp mills have shown finer-scale bio-diversity impacts related to mill effluents (Jones and Ellis, 1975; Pearson 1980 for review; Ostrovsky, 1987), but these patterns are not evident in the federal Environmental Effects Monitoring program data for pulp and paper mills URL: (ec.gc.ca/eem/english/PulpPaper/default.cfm). In addition, the Britannia mine near-field samples had uniformly low taxa numbers over a range of %TOC levels (%TN not measured), possibly due to metal toxicity (Hagan et al., 2004; G3, 2003). This pattern of reduced taxa number but not abundance in the area of historical tailings deposition near the mine was also noted 12 years after the mine closed (Ellis and Hoover, 1990).

Of the major taxonomic groups that are typically found in infaunal samples in British Columbia (bivalves, errantiate and sedentariate polychaetes, crustaceans), the bivalves in the present study tended to show the clearest responses to ambient and sedimentation gradients, although the reasons for these responses were not always clear. The relative rarity of infaunal bivalves at depths greater than 150-200 m in the Strait of Georgia has been observed coast-wide (Burd, 2006). Bivalve percent abundance was very strongly negatively correlated with $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, which we suggest is indicative of poor food quality. Since bivalves selectively ingest preferred organic material and reject the rest as pseudo-faeces (Taghon, 1982; Newell and Jordan, 1983; Macdonald and Ward, 1994; Bacon et al., 1998), there may simply not be enough food of acceptable quality for infaunal bivalves in the deeper areas of the Strait and fjords (or possibly in areas with very low sediment percent fines). This is supported by the relatively high correlation between bivalve abundance and organic flux weighted by $\delta^{15}\text{N}$.

The low bivalve abundance in the shallow areas may be an artifact of the limited number of shallow samples included in the database. For example, bivalve abundance was uniformly low in samples from 5 to 20 m depth near the Britannia mine site. Bivalves are known to bio-accumulate metals in their tissues, and a study of intertidal mussels has suggested toxicity responses in proximity to the Britannia mine drainage (Grout and Levings, 2001). A benthic study in Boundary Bay near the Washington border showed that infaunal bivalves were patchily abundant in shallow subtidal stations, but that substrate conditions (such as eel-grass beds) could potentially inhibit bivalve burrowing (Burd, 1992). Such erratic results suggest that more detailed sampling of shallow subtidal areas in the Strait of Georgia is required to understand biotic conditions relative to sedimentation .

Bivalves were the only group clearly depressed in samples taken near pulp and paper mills, suggesting that pulp mill deposits are not ideal for infaunal bivalve growth. This may be related to difficulty in burrowing through the fibrous organic material, or the low food quality of organic material in sediments. Several earlier studies of the impacts of wood waste in the Strait of Georgia tend to support the hypothesis that burrowing is impeded by wood fibre debris (Conlan, 1977; Conlan and Ellis, 1979; Ostrovsky, 1987).

5.0 Conclusions

Infaunal abundance and biomass in the Strait of Georgia cannot be readily predicted by static measurements of sediment particle size, organic content or water depth, because these measures do not take into account the rate or quality of organic input. Organic flux and quality are good

predictors of biotic abundance and biomass, particularly when outliers affected by sediment toxicity related to organic enrichment are considered separately. Higher deposition rates from terrestrial sources typically translate to higher overall labile organic input, supporting a high macro-faunal abundance and biomass, as well as dominance by infaunal bivalves. Relative proportions of organic and inorganic flux, as well as % carbonate, were also important to biota, suggesting that organic matter and other factors in riverine input support productive benthic assemblages in the Strait of Georgia. It is clear from this study that organic and inorganic flux to sediments and the type of substrate influence infaunal production, and that all of these factors need to be included when modeling biological impacts related to organic deposition (Cromey et al., 1998).

Predictions of faunal abundance and biomass based on organic flux and quality to sediments must be approached with caution in complex hydrographic/input areas such as Burrard Inlet, and in fjords where confounding factors such as basin stagnation are primary drivers of benthic productivity. In addition, shallow subtidal areas in the Strait of Georgia have not been adequately studied in terms of infaunal or sedimentation patterns.

Taxa number can be well predicted by %TN or rate of organic/inorganic flux under background conditions, as well as in situations of labile organic enrichment (Iona and Lions Gate outfalls).

Taxa number is much less predictable near pulp mills and in areas receiving acid mine drainage.

The composition of the benthic fauna varies dramatically throughout the Strait, as do sedimentation dynamics. Fauna that are best suited to continuous bottom transport of material

northward and downslope from the Fraser River delta are clearly not the same as those best suited to conditions with high, finer particulate deposition from the water column.

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Figure Captions

Figure 1. General locations of historical and AMP grab sample data, with overlying bottom bathymetry based on multibeam data (courtesy of Natural Resources Canada) for the main basin of the Strait of Georgia. Multibeam data are not available for the adjacent fjords. The locations of the nine AMP grab sample locations are shown as white dots (which correspond with the AMP core locations; see Fig. 2). Locations of pulp mills, outfalls and the Britannia Beach acid mine drainage site are included. Note FR denotes Fraser River.

Figure 2. Locations of historical and nine AMP cores from the Strait of Georgia. Historical core names from the original reports are listed in Table 2.

Figure 3. Total abundance, taxa number and abundance of dominant taxonomic groups for historical and AMP grab samples versus sample depth. Mean background values $\pm$ SE for each biological factor are superimposed for arbitrarily selected depth ranges (points are shown on the plot at the maximum depth for that range). Note that mean values do not include any data for samples taken near anthropogenic discharges.

Figure 4. Total abundance, taxa number and abundance of dominant taxonomic groups for historical and AMP grab samples versus sample percent silt/clay. Mean background values $\pm$ SE for each biological factor are superimposed for arbitrarily selected depth ranges (points are shown on the plot at the maximum depth for that range). Note that mean values do not include any data for samples taken near anthropogenic discharges.

Figure 5. Total abundance, taxa number and abundance of dominant taxonomic groups for historical and AMP grab samples versus %TOC. Mean background values $\pm$ SE for each biological factor are superimposed for arbitrarily selected depth ranges (points are shown on the plot at the maximum depth for that range). Note that mean values do not include any data for samples taken near anthropogenic discharges.

Figure 6. Total abundance, taxa number and abundance of dominant taxonomic groups for historical and AMP grab samples versus sample %TN. Mean background values $\pm$ SE for each biological factor are superimposed for arbitrarily selected depth ranges (points are shown on the plot at the maximum depth for that range). Note that mean values do not include any data for samples taken near anthropogenic discharges.

Figure 7. a. Geographic distribution of sediment fluxes and, b; sediment organic carbon flux rates from AMP and historical core data (as per Table 2). Locations of cores are shown as black dots on the figure and correspond to core locations shown in Figure 2. Locations of pulp and paper mills, outfalls and the Britannia Beach acid mine drainage are included for reference.

Figure 8. a; Geographic distribution of total abundance per grab, and b; bivalve abundance per grab for background locations in the Strait of Georgia, including several sample locations off southern Victoria in Juan de Fuca Strait. Locations of pulp and paper mills, outfalls and the Britannia Beach acid mine drainage are included for reference.

Figure 9. Geographic distribution of taxa number per grab for background locations in the Strait of Georgia, including Parry Bay and Macaulay point area in Juan de Fuca Strait. Locations of pulp and paper mills, outfalls and the Britannia Beach acid mine drainage are included for reference.

Figure 10. a; Distribution of carbon stable isotope composition ($\delta^{13}\text{C}$) relative to % TOC, and, b; distribution of nitrogen stable isotope composition ($\delta^{15}\text{N}$) relative to % TN for all depth layers in AMP cores (see Fig. 2 for locations of cores). Outfall samples show a divergence of old sediments deep in the core (pre-outfall) and newer sediments (post-outfall) based on $\delta^{15}\text{N}$ values, c; the progression from terrestrial (near the Fraser River) to marine (most northerly part of the Strait) organic deposition sources is shown in increasing $\delta^{15}\text{N}/\delta^{13}\text{C}$ ratios (see arrow in Fig. 10c). Cores 1 and 10 were from the most northern locations in the Strait, whereas cores 2-7 and 9 were collected in the southern basin (south of Texada Island – Fig. 1).

Figure 11. Best fit exponential regression line for log taxa number per grab versus organic/inorganic flux from AMP grab and core samples ($r^2=0.83$, $p<0.001$). Superimposed are data points for taxa versus %TN from the historical grab data for background locations and anthropogenic sites (exponential regression fits for these data; $r^2=0.66$, $p<0.001$).

Figure 12. Best fit regression line ($r^2=0.84$, $p<0.01$) for relationship of mean infaunal biomass versus buried organic carbon flux to sediments for 9 AMP locations (see Fig. 2 for AMP locations).

a

b

Figure 10

Table 1. Area, Depth, Year, Purpose of study and data source (reference) for historical and AMP grab sample data collected from 1988 to 2007.

Region	Depth (m)	Year	Purpose of study	References
West coast Vancouver Island, Alberni Inlet	25-45	2000	Ambient for pulp mill	Pulp and Paper Environmental Monitoring Program: ec.gc.ca/eem/english/PulpPaper/default.cfm
Southeast Strait of Georgia	60-70	1994-2004	Ambient for Outfall	CRD 2003, 2004, 2005, Paine et al. 2004
Howe Sound	5-20	2000	Brittania Beach, acid mine drainage	G3, 2003
Ecological Reserve 67, Southern Gulf Islands	60-70	1999	Background for pipeline	Burd et al., 2000
Mainland fjords	221-634	1988-1990	Ambient for deep fjords	Burd and Brinkhurst, 1992
Gorge Harbour, Cortes Island; Village Bay, Quadra Island	13-37m	2005	Reference related to oyster farm biodeposition	Barnes, 2007
Southeast Strait of Georgia	80	2000-2005	Ambient for Iona outfall	Bailey et al., 2003, McPherson et al., 2003, 2004a, 2005a, 2006a, 2007a
Outer Burrard Inlet	55-75	2002-2005	Ambient for Lions Gate outfall	McPherson et al., 2004b, 2005b, 2006b, 2007b
Northern Strait of Georgia: Johnstone St	30-100	2000-2002	BCMOE Fish farm monitoring	Wright et al., 2007 a-e,
Southeast Vancouver Island	1-25	2000	Background for pipeline landing	Seacology, 2001; Glaholt et al., 2002; Burd and Glaholt, 2000
Strait of Georgia	80-340	2003, 2004, 2006, 2007	Ambient monitoring for Strait of Georgia	Wright et al., 2008, McPherson et al., 2004c

Table 2. List of AMP cores (GVRD 1-7, 9,10) and historical cores, including original published names and coded labels used in Fig 2, year of collection and source for AMP (GVRD 1-7,9,10) and historical cores. Core locations are shown in Fig. 2.

Station	Code (Fig. 2)	Year Collected	Reference
17	Q	1993	Yunker et al., 1999; Johannessen et al., 2005a, b
21	O	1993	Yunker et al., 1999; Johannessen et al., 2005a, b
31	P	1993	Yunker et al., 1999; Johannessen et al., 2005a, b
A	R	1993	Yunker et al., 1999; Johannessen et al., 2005a, b
BB1	J	1990	Macdonald et al., 1992; Johannessen et al., 2005a, b
BC-2	G		Johannessen et al., 2005a, b
CM-3	K	1997	Johannessen et al., 2005a, b
CM-4	F	1997	Johannessen et al., 2005a, b
FD-12	L	1996	Shang et al., 1999; Johannessen et al., 2005a, b
FD-22	M	1996	Shang et al., 1999; Johannessen et al., 2005a, b
FD-3	N	1996	Shang et al., 1999; Johannessen et al., 2005a, b
HS-1	T	1990	Macdonald et al., 1992; Johannessen et al., 2005a, b
IND-VI	V	1994	Boyd et al., 1997; Johannessen et al., 2005a, b
PEI	S	1994	Boyd et al., 1997; Johannessen et al., 2005a, b
PM-V	W	1994	Boyd et al., 1997; Yunker et al., 1999; Johannessen et al., 2005a, b
SC	A	2001	Johannessen et al., 2005a, b
TC-1	U	1990	Macdonald et al., 1992; Johannessen et al., 2005a, b
TI	B	2001	Johannessen et al., 2005a, b
Vec04A-10	D	2004	Picard et al., 2006
Vec04A-11	I	2004	Picard et al., 2006
Vec04a-15	C	2004	Picard et al., 2006
Vec04A-16	E	2004	Picard et al., 2006
Vec04A-17	H	2004	Picard et al., 2006
GVRD-1	GVRD-1	2003	Wright et al., 2008
GVRD-2	GVRD-2	2003	Wright et al., 2008
GVRD-3	GVRD-3	2002	Wright et al., 2008
GVRD-4	GVRD-4	2002	Wright et al., 2008
GVRD-5	GVRD-5	2002	Wright et al., 2008

GVRD-6	GVRD-6	2003	Wright et al., 2008
GVRD-7	GVRD-7	2003	Wright et al., 2008
GVRD-9	GVRD-9	2007	Wright et al., 2008
GVRD-10	GVRD-10	2007	Wright et al., 2008

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Table 3

Table 3. Summary data for AMP core and grab samples (Wright et al. 2008). Sample locations are shown in Fig. 2. Biotic values are means for three replicate grabs for each location. All mean abundance values are per grab (0.1m²)

	GVRD-1	GVRD-2	GVRD-3	GVRD-4	GVRD-5	GVRD-6	GVRD-7	GVRD-9	GVRD-10
Sediment accumulation rate (g ^{cm} ⁻² a)	0.08	0.26	1.34	4.00 ⁺	0.64	2.70	0.32	0.16	0.059
Organic carbon flux (mg C ^{cm} ⁻² yr)	3.18	4.68	22.78	40.00	11.50	37.80	3.31	3.44	1.90
Inorganic flux (mg ^{cm} ⁻² yr)	74.42	255.32	1317.22	3960.00 ⁺	627.50	2662.20	311.69	156.56	48.19
Organic carbon/inorganic flux	0.043	0.018	0.017	0.010	0.018	0.014	0.011	0.022	0.038
Buried organic carbon flux (mg C ^{cm} ⁻² yr)	2.48	1.60	10.72	36.00	9.59	29.16	3.09	2.4	1.5
Oxidized organic carbon flux (mg C ^{cm} ⁻² .yr)	0.70	2.18	12.06	3.60	1.92	8.64	0.22	1.4	0.40
Organic carbon flux/ $\delta^{15}\text{N}$	0.48	1.00	10.00	11.20	1.93	6.57	0.59	0.49	0.27
Water depth of sample (m)	169	76	83	84	388	187	233	365	309
%TN*	0.51	0.15	0.12	0.09	0.19	0.16	0.13	0.27	0.43
%Carbonate*	0.03	0.10	0.15	0.19	0.08	0.09	0.09	0.06	0.07
%TOC*	4.07	1.54	1.15	0.91	1.65	1.32	1.01	2.19	3.60
%TOC/%TN*	8.01	10.41	9.53	10.31	8.55	8.26	8.08	8.11	8.37
Acid-volatile sulphides* ($\mu\text{mol/g}$)	2.00	2.00	11.47	0.20	0.10	1.33	0.10	N/A	N/A
$\delta^{15}\text{N}^*$	6.58	4.69	2.28	3.57	5.95	5.76	5.57	7.00	7.10
$\delta^{13}\text{C}^*$	-21.24	-23.85	-24.43	-24.83	-22.54	-21.62	-22.71	-21.34	-20.30
Mean taxa per grab	9.33	45.00	50.80	77.80	36.33	52.67	55.00	20.3	17.00
Mean total abundance	13	231	788	2015	84	640	233	75.3	32.30
Mean biomass (g ^{0.1m} ⁻²)	1.13	7.30	26.50	46.60	48.20	62.60	22.90	4.03	6.36
Mean number of holothuroids	2.33	0.33	0.50	2.83	7.67	2.50	22.67	3.33	1.67
Mean number of ophiuroids	0.00	0.00	4.44	18.67	1.67	2.33	1.33	0.00	0.00
Mean number of bivalves	0.00	100.67	521.44	1061.89	3.33	127.00	39.67	1.00	3.00
Mean number of gastropods	0.00	22.67	15.28	102.17	0.67	89.00	2.00	0.00	0.33
Mean number of errantiate polychaetes	4.67	19.33	45.83	56.83	14.67	31.67	36.33	7.66	6.00
Mean number of sedentary polychaetes	3.00	72.00	197.67	638.06	36.00	91.67	104.67	57.00	14.00
Mean number of crustaceans	0.00	8.67	1.83	78.72	3.00	279.00	15.33	1.00	1.30

+ this value is estimated (see results)

*surface sediment core layers – 1-2 cm

Table 4

Table 4. Pearson correlation coefficients between biotic and sediment factors for core/grab data for AMP locations from the Strait of Georgia; %polychaetes is proportion of abundance made up of all polychaetes; %bivalves is proportion of abundance made up of bivalves. All biotic factors are values per grab ($=0.1\text{m}^2$). All values were exploratory only, without any hypothesis testing. For reference, values > 0.755 would be considered significant at $p=0.05$ for testing the null hypothesis that the correlation coefficient was 0 for any given correlation.

	Number of Taxa	Total Faunal Abundance	Biomass (g)	Number of holothuroids	Number of ophiuroids	Number of bivalves	Number of gastropods	Number of errantiate polychaetes	Number of sedentariate polychaetes	Number of crustaceans	% polychaetes	% bivalve
Sedimentation rate ($\text{g cm}^{-2}\text{yr}^{-1}$)	0.74	0.92	0.85	-0.20	0.86	0.83	0.94	0.78	0.84	0.64	-0.45	0.7
Organic carbon flux ($\text{mg C cm}^{-2}\text{yr}^{-1}$)	0.71	0.90	0.87	-0.27	0.73	0.75	0.92	0.76	0.72	0.73	-0.58	0.6
Organic/inorganic flux	-0.90	-0.63	-0.66	-0.35	-0.45	-0.47	-0.51	-0.76	-0.54	-0.35	0.51	-0.5
Buried organic carbon flux ($\text{mg C cm}^{-2}\text{yr}^{-1}$)	0.69	0.86	0.89	-0.19	0.80	0.74	0.94	0.71	0.76	0.72	-0.46	0.5
Oxidized organic carbon flux ($\text{mg C cm}^{-2}\text{yr}^{-1}$)	0.47	0.63	0.46	-0.38	0.20	0.46	0.45	0.58	0.27	0.46	-0.68	0.5
Water depth of sample (m)	-0.53	-0.66	-0.13	0.29	-0.45	-0.63	-0.50	-0.62	-0.52	-0.18	0.65	-0.7
%TN*	-0.92	-0.67	-0.62	-0.24	-0.46	-0.53	-0.49	-0.80	-0.56	-0.29	0.54	-0.6
%Carbonate*	0.85	0.93	0.60	-0.10	0.85	0.94	0.63	0.92	0.91	0.16	-0.35	0.9
%TOC*	-0.92	-0.66	-0.64	-0.29	-0.45	-0.51	-0.49	-0.79	-0.54	-0.32	0.54	-0.6
%TOC/%TN*	0.58	0.62	0.22	-0.39	0.58	0.70	0.42	0.55	0.64	-0.07	-0.35	0.8
$\delta^{15}\text{N}^*$	-0.74	-0.80	-0.39	0.16	-0.56	-0.79	-0.40	-0.84	-0.66	-0.03	0.61	-0.9
$\delta^{13}\text{C}^*$	-0.79	-0.74	-0.40	0.03	-0.64	-0.77	-0.39	-0.81	-0.72	0.06	0.54	-0.8
Organic carbon flux/ $\delta^{15}\text{N}$	0.71	0.96	0.69	-0.31	0.78	0.90	0.73	0.86	0.81	0.41	-0.52	0.8
Acid-volatile sulphides ($\mu\text{mol/g}$)	-0.04	0.06	-0.23	-0.40	-0.07	0.21	-0.20	0.26	-0.02	-0.21	-0.36	0.6

* Surface sediment core layers – 1-2 cm