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Seasonal and spatial variations in the source and transport of sinking particles in the Strait of Georgia, British Columbia, Canada

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Abstract

Three sequential sediment traps were deployed at 150 m in the Strait of Georgia from March 1996 to February 1998, one at the southern end of the Strait, one located centrally, opposite the main channel of the Fraser River, and one to the north of the Fraser River channels. Subsequently, all three traps were moored at the central site on a single mooring (150, 225 and 300 m) from February 1998 to January 1999. The highest total flux in the <500 μm fraction (2.2 g cm^{-2} a^{-1}) was recorded at the southern station and the lowest at the northern station (0.044 g cm^{-2} a^{-1}). An annual flux peak at all three stations coincided approximately with the Fraser River freshet (May/June), and the southern station exhibited a second flux peak in September, which seemed not to be directly associated with the river's discharge. Lithogenic particles dominated the flux at all three stations, representing about 85% of the total flux at the southern and central stations and 60% at the northern station, although that proportion varied widely throughout the year at all three stations. According to stable isotope composition ($\delta^{13}C$ and $\delta^{15}N$), the majority of the biogenic material was marine-derived, particularly at the northern station (approximately 80% of organic matter marine-derived), with much of the variation in the trap samples explained by variation in the proportions of marine and terrigenous organic matter. However, a second source of variation was evident in the isotopic composition of the marine-derived organic matter, probably because of seasonal changes in nutrient availability, productivity and the length of the local food chain. As a result, the sinking organic matter in the Strait of Georgia can be described as a mixture of three end-members—terrigenous, marine (bloom) and marine (non-bloom). The flux and compositional data, together with data from sediment cores collected at the same locations, imply that most of the particles settle in the southern Strait, where they may then be transported northward along the bottom toward the central and northern stations.

Keywords: marine geochemistry; sediment traps; sediment transport and fate; stable isotopes

1. Introduction

Global continental margins are considered to play an important role in the production, processing and

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sequestration of organic carbon by the world ocean (Liu et al., 2000; Fasham, 2002; Ludwig et al., 1996). This relative importance to the organic carbon cycle is supported by high primary production, high influx of terrigenous matter and high rates of inorganic sediment fluxes to support burial. Perhaps even more importantly, these same regions are among the most vulnerable to global change, including disturbance of adjacent terrestrial drainage basins, eutrophication, contamination, invasive species and surface ocean warming. Our present understanding of how coastal systems process organic carbon is based on relatively few case studies mostly examining open continental shelves (e.g., Liu et al., 2000). Marginal enclosed seas provide crucial settings to study, partly because they are highly esteemed by humans and partly because the natural enclosed setting simplifies the construction of models and validation data sets. In specific cases, like the Strait of Georgia on the northwest coast of North America (Fig. 1), the coastal inland sea traps most of the terrigenous material supplied to it by the Fraser River, one of the world's great montane rivers (Milliman and Meade, 1983; Johannessen et al., 2003), thus starving the outer continental shelf of terrigenous organic carbon and sediments (Macdonald and Pedersen, 1991). Clearly, the role of the continental shelf in this case depends critically on the enclosed basin as a 'marginal filter.' The processes of transport, transformation and burial in coastal enclosed seas, which can be studied in detail using a variety of sampling techniques and geochemical tracers ($\delta^{13}C$, $\delta^{15}N$), are likely to

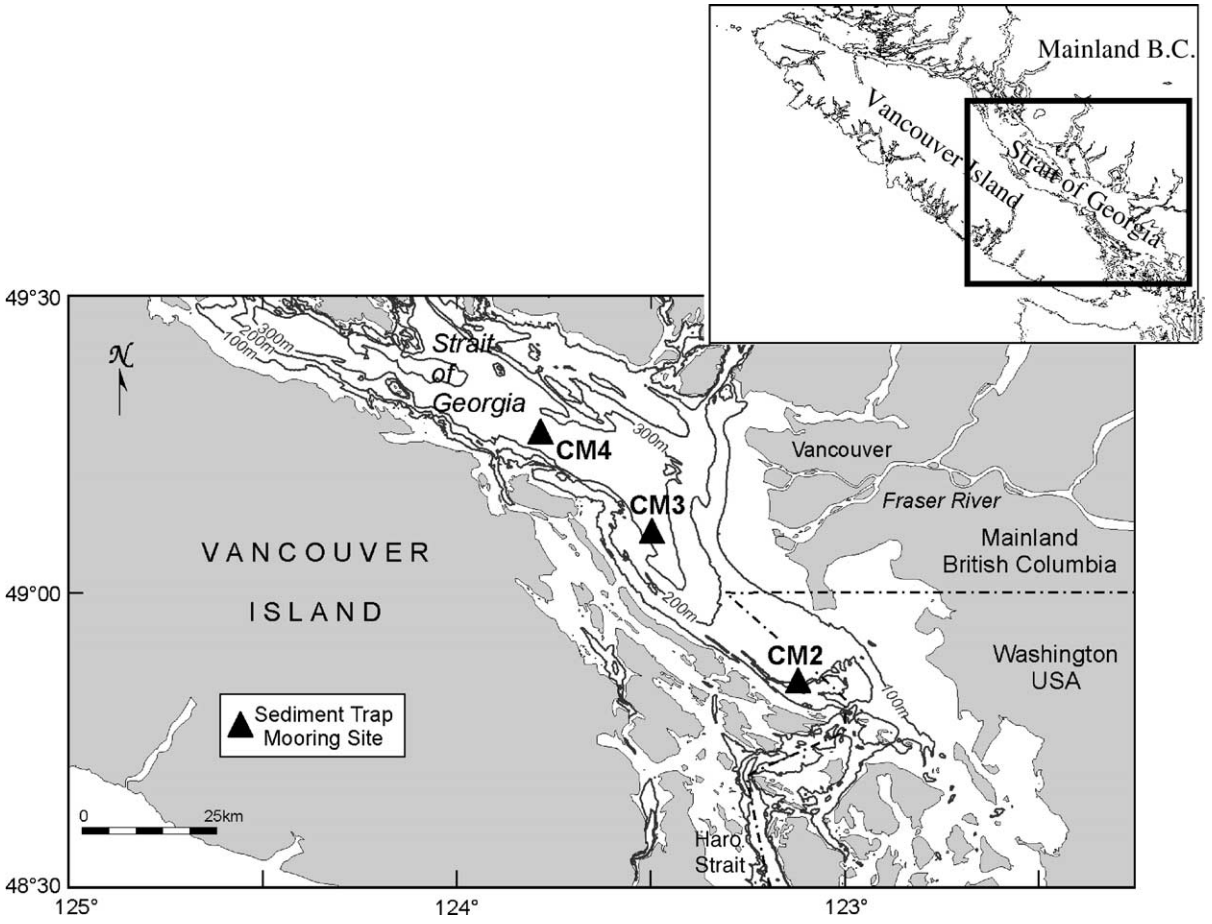

Fig. 1. The Strait of Georgia, showing sediment trap mooring locations.

enhance understanding of other regions where fewer data have been collected.

The fluxes of particles and particulate organic carbon to the Strait of Georgia are high, as is the rate of sediment accumulation (Johannessen et al., 2003). As a result, the Strait is net autotrophic with respect to particulate organic carbon, although the dominance of dissolved organic carbon may make the Strait slightly net heterotrophic overall (Johannessen et al., 2003). Sinking particles also carry with them many organic and inorganic contaminants. Determining the pathways of particles and organic carbon through the Strait of Georgia is of fundamental importance to understanding and modeling the fate of inorganic and organic carbon and contaminants in this system.

Rivers supply more than 80% of the particles that enter the Strait of Georgia (Johannessen et al., 2003). The Fraser River alone supplies 65–80% of the particles (Thomson, 1981; Waldichuk, 1957), and approximately half of the organic carbon, the remainder of which derives mainly from in situ primary production (Johannessen et al., 2003). Once in the Strait, particles are transported by tidal, wind-driven and estuarine currents (Waldichuk, 1957; Pharo and Barnes, 1976), slumps and debris flows (Mosher and Hamilton, 1998). In addition, periodic deep-water renewal (Masson, 2002) may transport particles into and within the Strait. River discharge, phytoplankton production and deep-water renewal are all strongly seasonal, so the type, number and location of sinking particles vary throughout the year.

1.1. Stable isotopes as geochemical indicators

Stable isotopes of carbon and nitrogen in organic matter are often used to infer the marine or terrigenous origin of sinking or sedimented organic matter in coastal waters (e.g. Fogel and Cifuentes, 1992; Hebbeln et al., 2000; Peters et al., 1978; Schubert and Calvert, 2001). Plants do not take up all isotopes of an element equally. In general they select the lighter isotope, although their ability to do so is limited by the isotopic composition of the available nutrients. Terrestrial plants and freshwater algae are isotopically lighter than marine phytoplankton, with $\delta^{13}C \sim -26‰$ and $\delta^{15}N \sim 3‰$ or 0‰ (where fertilizer made by the Haber process is used; Fogel and Cifuentes, 1992). The isotopic composition of marine phytoplankton is more variable but generally heavier, with $\delta^{13}C = -20$ to $-27‰$, and $\delta^{15}N \sim 8‰$ (Fogel and Cifuentes, 1992) or higher (e.g. Middelburg and Nieuwehuize, 1998; Schubert and Calvert, 2001). Therefore, in areas where sinking organic matter is derived from a mixture of marine and terrestrial sources, stable C and N isotopes can be used to assign a proportion to each source. However, other factors can affect the isotopic composition of organic matter.

Offshore, where marine phytoplankton and their products dominate the organic matter, variations in the stable carbon and nitrogen isotopes in sinking organic matter result mainly from seasonal changes in the isotopic composition of the algae. The $\delta^{13}C$ of sinking organic matter increases during a bloom, because as the phytoplankton draw down the preferred, isotopically-light $CO_{2(aq)}$, they begin to rely on bicarbonate, which is isotopically heavier (Ostrom et al., 1997; Rau, 1994). Consequently, $\delta^{13}C$ can be an indicator of productivity, or, by extension, of eutrophication (Struck et al., 2000). The $\delta^{15}N$ of sinking organic matter in fecal pellets or other particles also responds to changes in productivity and nutrient utilization. Upwelled nitrate is isotopically lighter than recycled ammonia, for example, so $\delta^{15}N$ of phytoplankton decreases as ammonia is depleted and phytoplankton rely more on nitrate (Altabet and McCarthy, 1986). The change in fractionation in response to changes in the availability of ammonia and nitrate can be observed in sinking particles and sediments (Altabet and Francois, 1994; Ostrom et al., 1997; Waser et al., 1998), particularly along a productivity gradient (Freudenthal et al., 2001). This makes $\delta^{15}N$ a useful indicator of paleoproductivity in areas where there is little terrestrial input (e.g. Farrell et al., 1995; Francois and Altabet, 1992). The $\delta^{15}N$ in sinking organic matter (mainly in the form of fecal pellets, detritus and sinking phytoplankton) also increases with the length of the local food chain, because $\delta^{15}N$ tends to increase by about 3‰ at each successive step up in trophic level (Hobson et al., 2002). The $\delta^{13}C$ also increases with trophic level, though at a rate of only about 1‰ per trophic level (Parsons and Chen, 1995). The $\delta^{13}C$ and $\delta^{15}N$ in sinking organic matter thus reflect a number of processes, which, especially in coastal environments where both

terrestrial and in situ production contribute organic matter, can confound interpretation, if either isotope is considered alone.

Here, we report seasonal variations in the flux and composition of sinking particles captured by sequential sediment traps moored at three locations in the southern and central Strait of Georgia. These are the first such data for the Strait of Georgia. From the sediment trap samples and from sediment cores collected at the same locations, we infer variations in the source of material sinking through the water column and suggest a general scheme of particle transport in the Strait. We also suggest a novel method to interpret stable isotopes of carbon and nitrogen that demonstrates the simultaneous effects of two processes—mixing of marine and terrigenous organic matter and seasonal variation in the isotopic composition of local phytoplankton.

2. Methods

The sediment trap deployment and subsequent sample splitting and analyses have been described in detail by O'Brien et al. (2000). One Baker sequential sediment trap (Baker and Milburn, 1983) was deployed at each of three stations at 150 m (Figs. 1 and 2; Table 1) for two years, with collection intervals of 8–20 days. All three traps were subsequently deployed on a single mooring (station CM3: 150 m, 225 m, 300 m) for a third year. The traps were cylindrical and had an aspect ratio of 5 (height=1 m; internal diameter=0.20 m). U.S. GOFS (Knauer and Asper, 1989) recommended the use of cylindrical traps, because they are less subject to collection biases than are conical traps. Gardner et al. (1997) found that cylindrical sediment traps did not over- or under-collect significantly at current velocities of 1–22 cm/s,

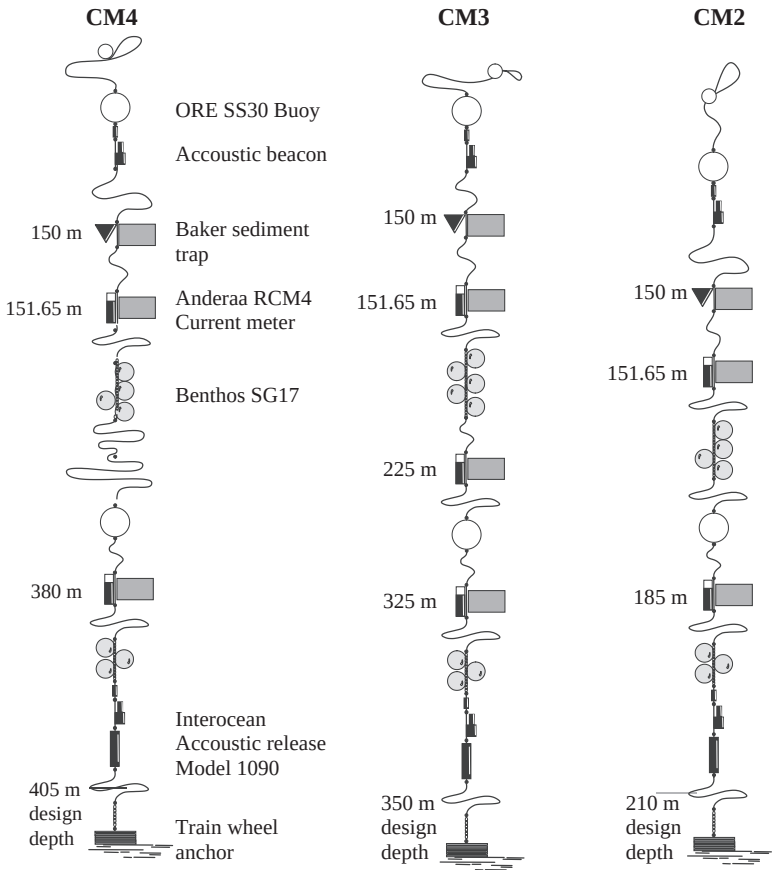

Fig. 2. Sediment trap mooring configuration, from O'Brien et al. (2000).

Table 1
Station locations and bottom and trap depths

Station	Latitude (°N)	Longitude (°W)	Bottom depth (m)	Trap depth (m)
CM2	48°50.837′ (48°50.803′–48°50.868′)	123°7.124′ (123°7.035′–123°7.283′)	211 (207–216)	150 (1996–1998)
CM3	49°6.052′ (49°5.980′–49°6.255′)	123°29.734′ (123°29.474–123°30.952′)	349 (342–365)	150 (1996–1999)
				225 (1998–1999)
				300 (1998–1999)
CM4	49°15.989′ (49°15.951′–49°16.006′)	123°46.587′ (123°46.478′–123°46.690′)	410 (408–417)	150 (1996–1998)

The moorings at stations CM2 and CM4 were each deployed six times and the CM3 mooring nine times, so the position of the moorings was not always precisely the same. The table shows the mean (and range of variation of) position and depth of each station.

although Baker et al. (1988) found that trapping efficiency decreased at current velocities greater than 12 cm/s. An Aanderaa RCM4 current meter attached to each mooring line 1.65 m below the top of each sediment trap measured current speed every 30 min for the entire period of deployment.

Prior to trap deployment each collection vial was poisoned with 200 mg of $HgCl_2$ to inhibit bacterial growth. Two grams of NaCl was added to each tube to generate a density gradient that minimized mixing of the sample with ambient seawater. Honeycomb baffles minimized turbulent flow over each trap to allow particles to settle into the trap. They also restricted the entry of large, swimming organisms (Gardner, 1980). After retrieval, the samples were sieved through a 500-μm mesh to remove any swimmers that had entered the traps, and the >500-μm fraction was saved for future analysis. The <500-μm portion of each sample was used in the analyses discussed in this paper.

Samples were rinsed with deionized, distilled water to remove salt, centrifuged, and then freeze-dried. Total dry weight flux was determined as the sample weight divided by the product of the trap collection area and the collection interval. Total carbon and total nitrogen were determined with a Carlo Erba CHN analyzer, carbonate carbon by coulometry in a UIC coulometer, and organic carbon by difference (analytical precision±3% for all). Biogenic silica was determined by laboratory personnel in the Department of Earth and Ocean Sciences at the University of British Columbia, using Na_2CO_3 extraction followed by molybdate blue spectrophotometry.

The carbon and nitrogen isotopic analyses were also performed at the University of British Columbia by VG PRISM isotope ratio mass spectrometry with a Carlo Erba CHN analyzer in line. The stable isotopic composition of carbon was reported as $\delta^{13}C$ (analytical precision±0.2‰), relative to the Peedee belemnite (PDB) international reference standard. That of nitrogen was reported as $\delta^{15}N$ (analytical precision±0.3‰), relative to air.

2.1. Calculation of biogenic flux

To calculate the biogenic flux (g m^{-2} d^{-1}), we assumed that the organic C occurred as CH_2O (=30/12×mass organic carbon) and the Si as $SiO_2 \cdot nH_2O$ (=2.4×mass biogenic Si; Mortlock and Froelich, 1989). We summed the fluxes (g m^{-2} d^{-1}) of N, CH_2O and $SiO_2 \cdot nH_2O$. The proportion of biogenic material (percent biogenic) could then be calculated as the ratio of the biogenic flux to the total flux in each trap sample (×100%), while the remainder of the material was assumed to be lithogenic.

2.2. Calculation of flux-weighted mean concentrations

Because the flux of particles and the concentration of all the measured components varied seasonally, the collection intervals did not all contribute equally to the total, annual flux of particles or of individual components (e.g. organic carbon). Therefore, to calculate mean annual concentrations, we multiplied the concentration of each component in each collection interval by the proportion of the annual flux collected during that interval, and then summed the weighted values. To calculate flux-weighted, mean daily concentrations, we divided the flux-weighted annual values by 365.25 days/year.

3. Results and discussion

3.1. Particle source

The flux of particles into the sediment traps was greatest at station CM2 (the southernmost station) and least at station CM4 (the northernmost; Table 2; Fig. 3; raw data reported by O'Brien et al., 2000). The pattern in the proportions of the biogenic components, organic C, N and biogenic Si, was opposite to that, with the highest proportions of those components at station CM4 (Table 2; Fig. 4). The flux-weighted, annual average proportion of biogenic material, calculated as described in the methods section, was much higher at station CM4 (~41%) than at CM3 (~13% at 150 m; ~19% at 225 and 300 m) or CM2 (~15%; Table 2). These patterns probably reflect the influence of the Fraser River, the main source of inorganic particles to the Strait (annual Fraser River particle flux 19×10^9 kg; Thomas and Bendell-Young, 1999). Satellite images of interpreted suspended sediment concentration at the surface of the Strait (J. Gower, unpublished Advanced Very High Resolution Radiometer results, 2003; http://www-sci.pac.dfo-mpo.gc.ca/osap) show that the Fraser River plume can reach all three stations (Fig. 5). The plume usually extends north–south more than east–west, meaning that it reaches stations CM2 and CM3 more often than CM4. The timing of the Fraser River freshet also coincides with that of the summer maximum particle flux at stations CM2 and CM3, while it precedes that at station CM4 by about a month (Fig. 6). (The daily particle flux from the Fraser River is highest at the beginning of the freshet; Kostaschuk et al., 1989).

The fluxes of organic carbon and nitrogen were strongly correlated with each other ($r^2\geq0.9$) at all three stations, as were those of biogenic Si and

Table 2
Flux-weighted average daily and annual chemical composition and flux of sinking particles

	CM2-150 m	CM3-150 m	CM3-225 m	CM3-300 m	CM4-150 m
	Mean (range)	Mean (range)	Mean (range)	Mean (range)	Mean (range)
Organic C daily flux (g m^{-2} d^{-1})	1.0 (0.43–2.3)	0.18 (0.043–0.81)	0.15 (0.083–0.27)	0.24 (0.080–0.46)	0.085 (0.016–0.21)
Organic C %	1.8 (0.97–4.0)	2.3 (0.71–7.5)	2.5 (1.7–4.7)	2.4 (1.6–3.3)	7.3 (2.9–19)
Biogenic Si daily flux (g m^{-2} d^{-1})	2.5 (1.0–5.5)	0.34 (0.051–1.5)	0.30 (0.15–0.85)	0.51 (0.17–1.2)	0.10 (0.021–0.88)
Biogenic Si %	4.2 (2.6–8.2)	4.4 (1.6–12)	5.0 (2.7–9.2)	5.1 (3.3–8.7)	9.0 (3.9–28)
N daily flux (g m^{-2} d^{-1})	0.13 (0.052–0.29)	0.022 (0.0063–0.095)	0.019 (0.011–0.036)	0.030 (0.012–0.064)	0.011 (0.0021–0.024)
N %	0.22 (0.14–0.51)	0.29 (0.090–1.1)	0.32 (0.18–0.68)	0.30 (0.20–0.45)	0.90 (0.38–2.3)
Daily biogenic flux (g m^{-2} d^{-1})	8.69 (3.6–19)	1.3 (0.24–5.6)	1.1 (0.62–2.7)	1.9 (0.62–4.2)	0.47 (0.12–2.6)
Total biogenic %	15 (10–24)	13 (6.1–44)	19 (11–32)	19 (13–29)	41 (18–81)
Daily lithogenic flux (g m^{-2} d^{-1})	50 (19–150)	8.7 (0.33–86)	4.9 (1.5–10)	8.1 (2.4–16)	0.74 (0.12–3.6)
Organic C/N annual average (atomic ratio)	9.5 (4.8–12)	9.6 (6.3–12)	9.4 (6.6–12)	9.4 (7.7–11)	9.4 (6.7–15)
Organic C/N Apr.–Aug. (atomic ratio) with standard deviation	9 (1)	9.2 (0.9)			9.4 (1.7)
Organic C/N Oct.–Feb. (atomic ratio) with standard deviation	9.9 (0.4)	10 (1)			9.4 (1.1)
Total, annual trap flux (g m^{-2} a^{-1})	2.2×10^4	0.42×10^4	0.22×10^4	0.37×10^4	0.044×10^4
Sediment core accumulation rate (g m^{-2} a^{-1}) at same stations	2.3×10^4	1.6×10^4			0.26×10^4

"Biogenic flux" and "biogenic %" represent the sum of the fluxes (g $m^{-2}d^{-1}$) or percent composition (%) of N, CH_2O (calculated as organic C×30/12, the ratio of the molecular masses of CH_2O and C) and $SiO_2\cdot nH_2O$ (calculated as biogenic Si×2.4; Mortlock and Froelich, 1989). Lithogenic flux was determined as the difference between the total and biogenic fluxes. Average daily fluxes were calculated for the whole period of deployment of each trap, i.e. stations CM2 and CM4, 2 years; CM3-150 m, 3 years; CM3-225 m and CM3-300 m, 1 year. The range of each flux or percent composition (except for the seasonal average C/N ratio) is reported, rather than the standard deviation, because the actual range of variability in flux and composition of the sinking particles is much greater than measurement error. The standard deviation is reported for the Apr.–Aug. and Oct.–Feb. average C/N ratios, because it was used in a *t*-test to compare the seasonal values. The sediment core accumulation rates are from Johannessen et al. (2003).

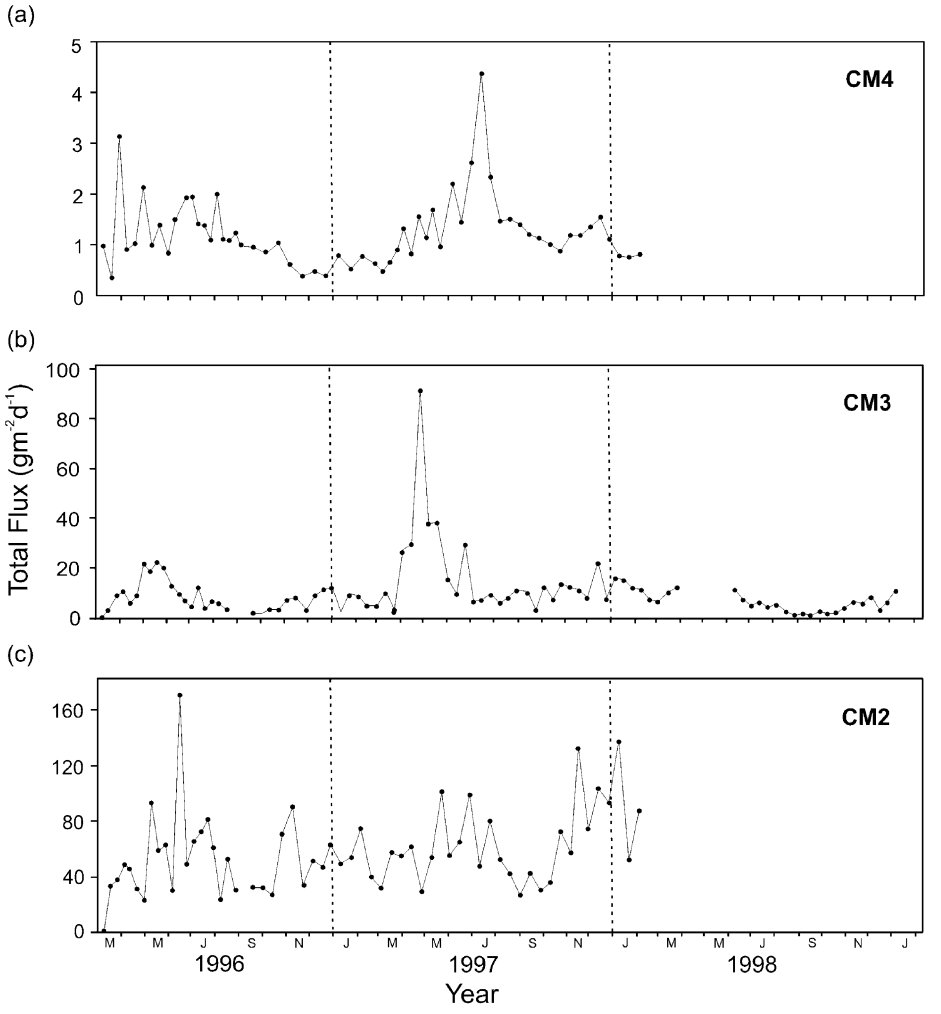

Fig. 3. Total dry mass flux into 150 m sediment traps, March 1996–January, 1999; (a) station CM4, (b) station CM3 (c) station CM2. Note different scales on the vertical axes.

organic C at stations CM2 and CM3 (CM2: r^2=0.77, n=58; CM3: r^2=0.80, n=87) although biogenic Si and organic C were only weakly correlated at station CM4 (r^2=0.24, n=60). The proportion of organic C, biogenic Si and N collected in all the traps was highest in the spring and autumn. At stations CM2 and CM3, these proportions were low during the May/June Fraser River freshet, while at station CM4 they remained high at that time. Taken together, the total flux, proportions of organic C, N, biogenic Si and total biogenic material, Fraser River plume extent and timing of the particulate flux maximum all suggest that sinking particles at station CM4 are less strongly influenced by the Fraser River than are those at the two stations further south.

Not all of the seasonal and spatial variation is related directly to the Fraser River. At station CM2 there is a second flux peak in November/December (Fig. 3), when the Fraser River's flow is low. This peak may be related to resuspension of particles by winter storms, or perhaps to an influx of particles along the bottom of Juan de Fuca Strait and through the Haro Strait as a result of a deep water renewal event. There is also another source of biogenic material, besides the Fraser and other rivers. A recent mass balance for the Strait of Georgia suggested that

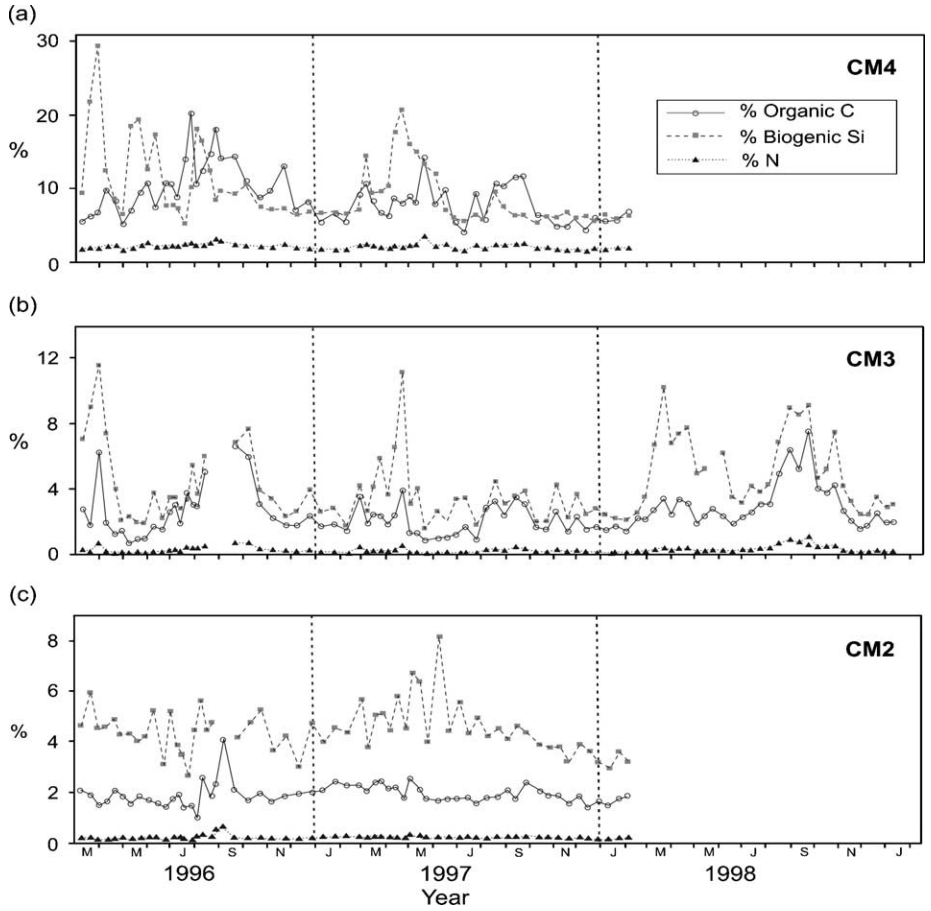

Fig. 4. Percent organic carbon, biogenic silica and nitrogen into 150 m traps, March 1996–January, 1999; (a) station CM4, (b) station CM3, (c) station CM2. Note different scales on vertical axes.

primary production was at least as large a source of particulate organic carbon to the Strait as the Fraser River (Johannessen et al., 2003). The maximum primary productivity in the Strait usually occurs in May (Harrison et al., 1983), and the maximum flux of algae-derived particulate organic carbon out of the photic zone can be delayed by as much as two months after primary production peaks (Stephens et al., 1967). Although the maximum biogenic flux coincides with the Fraser River freshet at stations CM3 and CM2, a large portion of that flux may be fallout from the spring bloom.

Phytoplankton productivity in the Strait of Georgia is not entirely independent of the Fraser River's discharge. The Fraser River discharges about 50 tonnes of nitrogen per day, the sum of its agricultural, sewage and natural inputs (Mackas and Harrison, 1997). This contribution pales in comparison with that of upwelling and estuarine inflow into the Strait of Georgia, Juan de Fuca Strait and the Strait of Georgia from the Pacific Ocean (2600–2900 tonnes/day; Mackas and Harrison, 1997). However, Yin et al. (1997) demonstrated that entrainment of subsurface nitrate and the shallowing of the pycnocline caused by strong discharge from the Fraser River can increase the concentration of nitrate in the euphotic zone by a factor of five and thereby maintain the bloom longer.

The flux-weighted, annual average organic C/N molar ratio of about 9.5 measured in all the traps falls between those of purely marine (6 locally, Drysdale, 1990; in general 6.6, Redfield et al., 1963) and purely terrigenous (>20, Emerson and Hedges, 1988; Born-

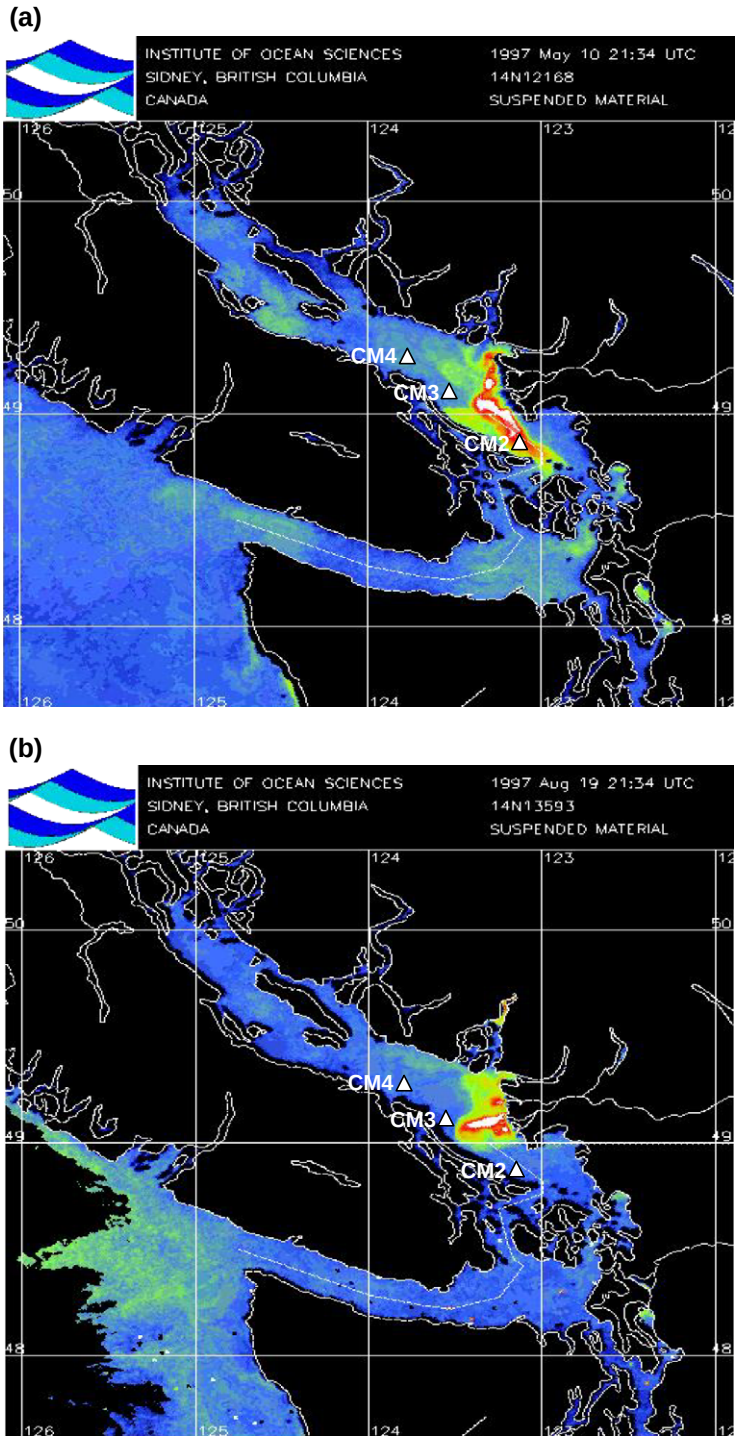

Fig. 5. Satellite images of suspended sediment concentrations in the Strait of Georgia, from the Advanced Very High Resolution Radiometer aboard a NOAA weather satellite, showing variation in the direction of the plume's sediment transport: (a) the plume turns south out of the mouth of the Fraser River, May 10, 1997; (b) the plume extends westward, across the strait, August 19, 1997. Images courtesy of J. Gower, Institute of Ocean Sciences, Sidney, B.C., May 2003. Similar images are posted at http://www-sci.pac.dfo-mpo.gc.ca/osap.

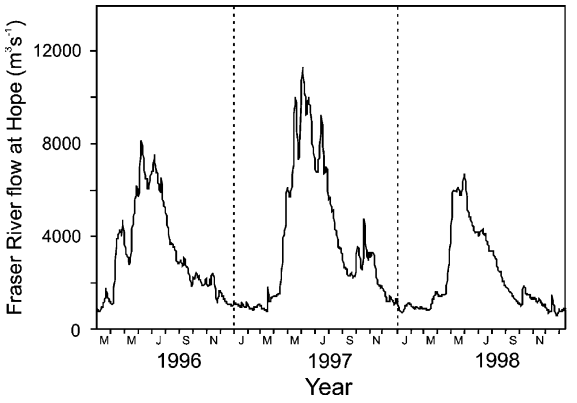

Fig. 6. Fraser River water flow measured at Hope, about 150 km upstream of the river mouth, during the sediment trap deployment. Data from Environment Canada, Water Survey of Canada, 2002 (unpublished data).

hold, 1978; Macdonald et al., 1991) organic matter. It is similar to the C/N ratio in cores collected at the sediment trap mooring sites (Table 2), although those varied more among stations. It is the same as the C/N ratio previously determined in two sediment cores collected in the central Strait of Georgia (9.5±1.0; Macdonald et al., 1991) and similar to that of surface sediments throughout the central and southern Strait (9–10; Gordon, 1997). At stations CM2 and CM3 the C/N ratio was significantly higher from October to February than from April to August ($p<0.05$, $n=49$ and 71), possibly implying a higher proportion of terrigenous organic matter in the winter than in the summer at those stations. This observation might also reflect the sinking of N-depleted phytoplankton in the winter. At station CM4 the C/N ratio did not vary significantly with season ($p=5\%$; $n=51$; Table 2), indicating a relatively constant proportion of terrigenous organic matter year-round at that site.

The biogenic Si/organic C ratio peaked just before the maximum particle flux at stations CM3 and CM4 (data not plotted), possibly as a result of the spring phytoplankton bloom, during which diatoms would have made up a larger than usual proportion of the flux. At station CM2, that ratio did not exhibit a clear seasonal signal. The average biogenic Si/C molar ratios at the three stations (CM4 0.28, CM3 0.91, CM2 0.89) are all considerably higher than the average ratio determined by Brzezinski (1985) for 27 species of marine diatoms (0.13±0.04). The reason for this is unclear. It could reflect preferential degradation of organic carbon over biogenic Si as the particles fall through the water column. If so, the process which controls the degradation must be relatively constant, since the fluxes of those two components are so highly correlated, at least at stations CM2 and CM3. Alternatively, there could be another source of biogenic Si in the Strait, or diatoms in this area might have a higher Si/C ratio than those in Brzezinski's study.

The maximum contribution from local primary production can be determined by comparing the expected flux of POC from phytoplankton with that calculated from the traps. The annual average flux of sinking particulate organic carbon, POC, to the 150 m traps was 31 $gCm^{-2}a^{-1}$ at station CM4, 68 $gCm^{-2}a^{-1}$ at station CM3 and 380 $gCm^{-2}a^{-1}$ at station CM2. In comparison, based on the Harrison et al. (1983) estimate of 280 $gCm^{-2}a^{-1}$ for average primary productivity in the Strait of Georgia, we expect 33 $gCm^{-2}a^{-1}$ of sinking POC [see Johannessen et al., 2003: 280 $gCm^{-2}a^{-1}$ primary productivity×35% "new production" (30–40% locally, Mackas and Harrison, 1997)×1/3 sinking POC (Durrieu de Madron et al., 2000)]. If that value is correct, all the organic carbon that reaches the 150 m trap at station CM4 could be derived from in situ primary production, while the CM3 and CM2 traps must have another significant source of organic C—most likely the Fraser River, which discharges approximately 170×10^6 kg/a of particulate organic C (Johannessen et al., 2003). The comparison of the sinking fluxes with the rate of primary production should be interpreted with caution, however, since patchiness in phytoplankton distribution makes it difficult to establish a robust average estimate of the rate of primary production for the Strait (Parsons et al., 1980, 1981; Mackas and Harrison, 1997).

3.2. Stable isotopes of carbon and nitrogen: source and seasonal composition of particles

The stable isotopic composition of the sinking particles reveals a mixture of sources of organic matter that varies seasonally and with location. Because marine-derived organic matter tends to be isotopically heavier than terrigenous organic matter, some of the seasonal and high-frequency variability in $\delta^{13}C$ and $\delta^{15}N$ (Fig. 7) probably results from changes

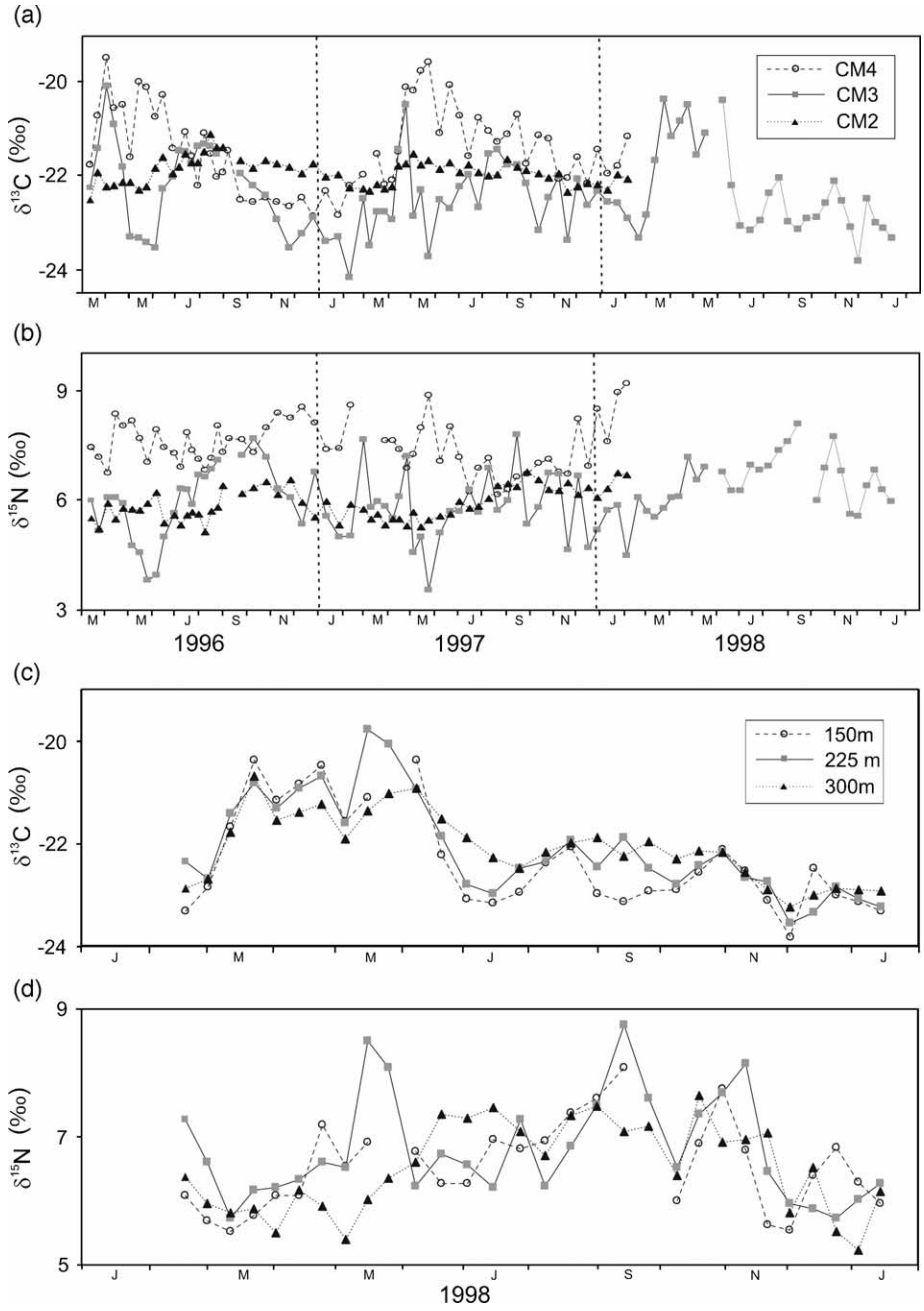

Fig. 7. Stable isotope time series; (a) $\delta^{13}C$ in all three 150 m traps, (b) $\delta^{15}N$ in all three 150 m traps, (c) $\delta^{13}C$ in 150 m, 225 m and 300 m traps at station CM3, (d) $\delta^{15}N$ in 150 m, 225 m and 300 m traps at station CM3.

in the degree of dominance of terrigenous (vs. marine-derived) organic matter in the traps. In particular, abrupt highs in $\delta^{15}N$ or $\delta^{13}C$ at station CM4 often coincided with lows at station CM3 (e.g. May, 1997; February, 1998), suggesting that the principal influence of the Fraser River had switched from one station to the other, as wind changed the position of the plume.

There was some inter-annual variability in the isotopic composition, especially at station CM3. For example, both $\delta^{13}C$ and $\delta^{15}N$ were higher in 1998 than in the preceding two years at that station. This may have been due to a decrease in the proportion of terrigenous material as a result of the low 1998 Fraser River flow that followed the 1997 El Niño. However, because several factors can change the $\delta^{13}C$ and $\delta^{15}N$ of sinking organic matter, as discussed in the introduction, it is difficult to draw strong conclusions from either isotope individually.

Together, the two isotopes provide a more incisive view of the source of the organic matter. A plot of $\delta^{13}C$ against $\delta^{15}N$ in the sinking organic matter (Fig. 8a) shows a positive correlation between the two isotope ratios, although there is considerable scatter about the central trend. Suspended sediment from the Fraser River falls in the low $\delta^{15}N$, low $\delta^{13}C$ corner of the plot. The variation from light to heavy isotopic composition in Fig. 8a is interpreted to represent mixing between terrigenous and marine end-members (cf. Peters et al., 1978). The marine–

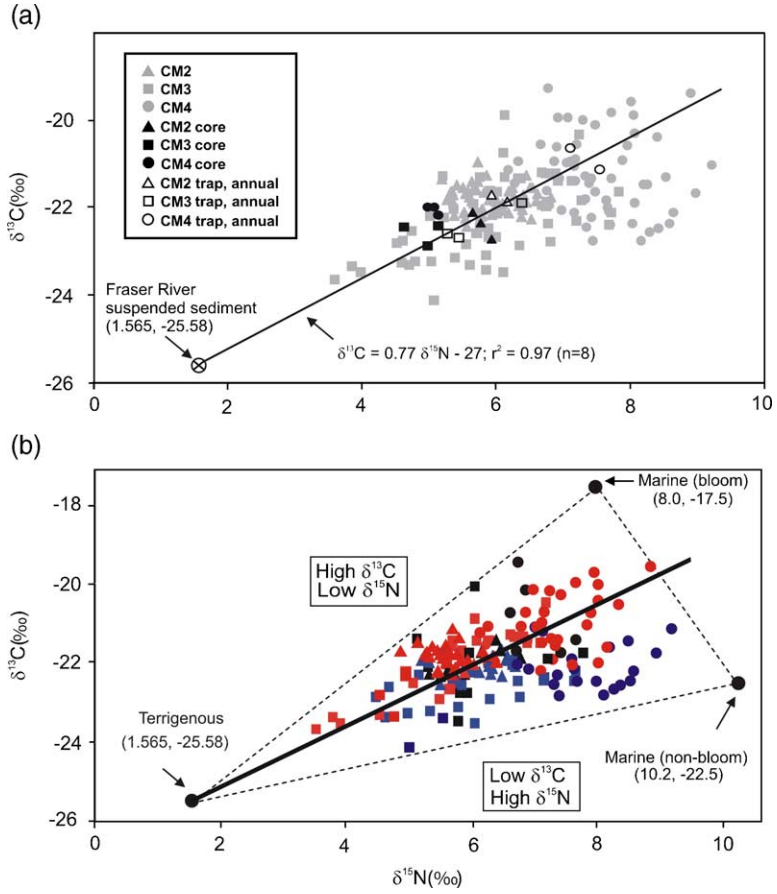

Fig. 8. (a) Stable isotopic composition of sinking organic matter at all three stations, March 1996–January 1999, showing flux-weighted, annual average $\delta^{13}C$ and $\delta^{15}N$ for each trap for each year of deployment, and $\delta^{13}C$ and $\delta^{15}N$ of sediments at three depths in a sediment core collected at each trap mooring site (Table 3). The terrigenous–marine mixing line was calculated as a regression on the composition of Fraser River suspended sediment collected by Environment Canada and the flux-weighted, annual average isotopic composition of each trap in each year of deployment. (b) Seasonal variation in stable isotopic composition of sinking organic matter. Summer (April–August) data are plotted in red, winter (October–February) in blue. Data from March and September are marked in black, because the change from summer to winter properties (or the reverse) occurred during those months. The isotopic composition of the Fraser River suspended sediment sample was used as the terrigenous end-member. The marine (bloom) and marine (non-bloom) end-members were chosen to provide the other two vertices of a triangle that encloses all the data, as described in the text.

terrigenous mixing line was calculated as a linear regression on the flux-weighted, annual average isotopic composition of the organic matter in the traps (marked as open symbols in Fig. 8a) and the isotopic composition of the Fraser River suspended sediment ($\delta^{13}C$=0.77 $\delta^{15}N$-27; r^2=0.97; n=8). Data from station CM4 fall closest to the marine end of the line, which is consistent with the smaller influence of the Fraser River at that station indicated by the flux and chemical composition data. The isotopic composition of organic matter from station CM3, opposite the main mouth of the Fraser River, varies widely along the mixing line, from dominantly marine to dominantly terrigenous. The CM2 data are grouped tightly in the middle of the data set. The low variability in the isotopic composition of organic matter at station CM2 may be a consequence of the low and relatively constant proportion of biogenic material at that station. Resuspension of bottom sediments by strong currents at that station might also smooth out high-frequency variations in the proportion of terrigenous organic matter at station CM2.

Although the observed, positive relationship between $\delta^{13}C$ and $\delta^{15}N$ is consistent with the mixing of terrigenous and marine end-members described by Peters et al. (1978), previous sediment trap work nearby has shown the opposite trend. Working on the continental shelf, off the west coast of Vancouver Island, Wu et al. (1999) and Peña et al. (1996) observed that $\delta^{13}C$ maxima in the sinking particles coincided with minima in $\delta^{15}N$. Wu et al. (1999) explained the high $\delta^{13}C$, low $\delta^{15}N$ in summer and low $\delta^{13}C$, high $\delta^{15}N$ in winter as the result of nano-phytoplankton dominance and a long food chain in the winter, and high productivity, dominance of diatoms and upwelling of ^{15}N-light nitrate in the summer. An additional factor might be that, with fewer zooplankton to "package" phytoplankton in the winter, the phytoplankton might sink slowly, allowing more time for bacteria to remineralize the organic matter and further increase the $\delta^{15}N$ of the sinking particles (F. Whitney, personal communication).

To resolve the apparent contradiction, and since the effects described by Wu et al. (1999) and Peña et al. (1996) are seasonal, we divided our data into "summer" and "winter" collection intervals. We defined summer and winter as April–September and October–March, respectively, in accord with a division made by Timothy et al. (2003), based on observations of fecal pellet colour in Saanich and Jervis Inlets (Sancetta, 1989). Plotting the summer and winter data as separate series (Fig. 8b) shows a clear isotopic variation with season. In general, the winter data in Fig. 8b (blue points) fall in the high $\delta^{15}N$/low $\delta^{13}C$ area of the plot, and the summer data (red points), toward the opposite corner. To highlight the seasonal difference, data from September and March, the months on the cusp of the seasonal change, are marked in black. The seasonal average isotopic composition for sinking organic matter at each station is reported in Table 3. There is some overlap in the plot between the summer and winter points, but the general separation of data by season is too great to represent random variation.

Temperature can affect $\delta^{13}C$ in sinking particles. The $\delta^{13}C$ of sinking particles is inversely related to $[CO_2]_{aq}$ (e.g. Lourey et al., 2004), which, in turn, is inversely related to temperature (Weiss, 1974). Using equilibrium solubility coefficients of CO_2 (Weiss, 1974) for salinity 30 and surface-water temperatures of 8 °C and 18 °C for winter and summer, respectively (R. Thomson, Institute of Ocean Sciences, unpublished data), the temperature change could shift $\delta^{13}C$ in the sinking particles from −25.5‰ in winter to −21.9‰ in summer. Although the absolute values of the calculated $\delta^{13}C$ do not match those observed, this shift would be sufficient to explain the observed seasonal separation in the $\delta^{13}C$ data. However, that calculation assumes that the surface water reaches equilibrium with the atmosphere, and CO_2 has an equilibration time with seawater of about a year (Broecker and Peng, 1982). When seawater is essentially isolated from the atmosphere, the temperature effect acts in the opposite direction: increased temperature shifts the dissolved inorganic carbon equilibrium toward CO_2, increasing $[CO_2]_{aq}$, and decreasing $\delta^{13}C$ (Lourey et al., 2004). In the Strait of Georgia, where the uppermost 30 m of water is replaced about once a month by strong estuarine circulation (Thomson, 1981), the surface water is probably not in equilibrium with the atmosphere with respect to CO_2. Seasonal variation in nutrient utilization, as proposed by Wu et al. (1999) for the nearby, outer continental shelf, is more likely to have caused the observed summer increase in $\delta^{13}C$. This con-

Table 3
Seasonal average $\delta^{13}C$ and $\delta^{15}N$ for sinking organic matter in all sediment traps, and $\delta^{13}C$ and $\delta^{15}N$ in organic matter from three depths in cores taken at the trap mooring stations

Station	Season in trap, or depth in core	Av. $\delta^{13}C$ (‰)	Av. $\delta^{15}N$ (‰)	*n*	% terrigenous	% summer marine	% winter marine	% summer (% summer+% winter)
CM2	Summer (trap)	−21.81 (0.29)	5.68 (0.31)	29	42 (3)	40 (5)	18 (7)	0.69 (0.10)
	Winter (trap)	−22.03 (0.20)	6.19 (0.38)	20	38 (3)	33 (4)	29 (7)	0.53 (0.09)
	3–4 cm (core)	−22.22	5.56	1	45	33	21	0.61
	12–14 cm (core)	−22.43	5.68	1	45	29	26	0.53
	30–35 cm (core)	−22.76	5.83	1	45	22	33	0.41
CM3	Summer—150 m (trap)	−22.03 (0.90)	5.96 (0.98)	41	40 (13)	34 (12)	25 (12)	0.58 (0.16)
	Winter—150 m (trap)	−22.85 (0.53)	6.08 (0.89)	31	42 (10)	19 (8)	38 (12)	0.34 (0.16)
	Summer—225 m (trap)	−21.47 (0.99)	6.75 (0.73)	14	30 (10)	39 (15)	31 (12)	0.55 (0.19)
	Winter—225 m (trap)	−22.84 (0.43)	6.66 (0.82)	12	37 (10)	16 (5)	47 (10)	0.25 (0.08)
	Summer—300 m (trap)	−21.67 (0.49)	6.55 (0.72)	13	33 (7)	37 (11)	30 (15)	0.56 (0.20)
	Winter—300 m (trap)	−22.72 (0.36)	6.42 (0.71)	10	39 (8)	19 (5)	42 (9)	0.32 (0.09)
	3–4 cm (core)	−22.52	5.05	1	52	31	17	0.65
	12–14 cm (core)	−22.54	4.53	1	57	34	9	0.80
	30–35 cm (core)	−22.91	4.88	1	55	26	19	0.57
CM4	Summer (trap)	−20.97 (0.74)	7.42 (0.61)	29	21 (8)	44 (12)	35 (11)	0.55 (0.14)
	Winter (trap)	−22.09 (0.56)	7.84 (0.76)	19	22 (8)	22 (11)	57 (14)	0.28 (0.15)
	3–4 cm (core)	−22.15	4.99	1	51	38	11	0.77
	12–14 cm (core)	−22.29	5.04	1	51	35	14	0.72
	30–35 cm (core)	−22.15	4.89	1	52	39	10	0.80

The fractions of terrigenous, summer marine and winter marine organic matter were calculated as described in the text using three end-members (terrigenous: $\delta^{15}N$=1.565‰, $\delta^{13}C$=−25.58‰; marine summer: $\delta^{15}N$=8.00‰, $\delta^{13}C$=−17.50‰; marine winter: $\delta^{15}N$=10.20‰, $\delta^{13}C$=−22.50‰). "Summer" refers to April–August, "winter," to October–February. March and September data are excluded, as discussed in the text. Values in brackets represent one standard deviation (calculated on "*n*" samples) of the calculated mean values; standard deviations are not given for the core samples, since only one sample from each depth was analyzed. The analytical precision of the isotopic measurements was ±3%.

clusion is further supported by the observation that the seasonal variation is greatest among data at the marine end of the mixing line (Fig. 8b), where phytoplankton are expected to have the greatest influence.

The variation in the measured isotopic composition of the sinking organic matter, therefore, results from the combined effects of mixing of terrigenous and marine organic matter (along the mixing line), and seasonal, productivity-related variations in the marine portion (perpendicular to the mixing line). To quantify the contribution of each process to the observed isotopic composition, we have described the data as the mixing of three end-members: terrigenous, marine (high $\delta^{13}C$/low $\delta^{15}N$) and marine (low $\delta^{13}C$/high $\delta^{15}N$). The terrigenous end-member represents organic matter either from land or formed in the river, both of which sources tend to be isotopically depleted, as discussed in the introduction to this paper. The marine (high $\delta^{13}C$/low $\delta^{15}N$) end-member represents organic matter dominantly produced by phytoplankton and formed when $[CO_2]_{aq}$ was low (resulting in high $\delta^{13}C$) and the food chain was short and based more on nitrate than at other times (resulting in low $\delta^{15}N$). Since these are the conditions that prevail during a phytoplankton bloom, we will refer to the two marine end-members hereafter as marine (bloom) and marine (non-bloom).

We took the isotopic composition of the Fraser River suspended sediment sample ($\delta^{15}N$=1.565, $\delta^{13}C$=−25.58) as the terrigenous end-member, while the marine (bloom) and marine (non-bloom) end-members ($\delta^{15}N$=8.0, $\delta^{13}C$=−17.5 and $\delta^{15}N$=10.2, $\delta^{13}C$=−22.5, respectively) were chosen by eye to allow the three values to form the vertices of the smallest triangle that encloses all the data (Fig. 8b). Note that a line joining the summer and winter marine end-members is not exactly orthogonal to the mixing line. The two marine end-members do not represent a pure culture of a particular type of phytoplankton or a specific nutrient pool; rather, they represent the extremes observed over three years in the Strait of Georgia.

The $\delta^{13}C$ value of the most "marine" datum (CM4 May 21, 1997: $\delta^{15}N$=8.87‰, $\delta^{13}C$=−19.58‰) is similar to that determined as the marine end-member in Strait of Georgia sediments by Macdonald et al. (1991; −19.7‰) from a combination of C/N ratios and $\delta^{13}C$ measurements. It is also similar to the $\delta^{13}C$ marine end-member determined for station CM4 ($\delta^{13}C$=−19.04‰) using Timothy's (2001) method, which uses a regression of $\delta^{13}C$ on percent biogenic Si and accounts for diatomaceous and non-diatomaceous marine organic matter. There is no other published, local, marine end-member value of $\delta^{15}N$ for sinking particles or sediments. However, Peters et al. (1978), working in sediments of Washington's outer continental shelf, reported a marine–terrigenous trend in their data that they compared with a Namibian marine end-member ($\delta^{15}N$=9.2‰, $\delta^{13}C$=−20‰) that was similar to our most marine point.

The fractional, end-member composition of each datum was determined by solving the following three equations,

$$F_n + F_b + F_t = 1$$

$$\delta^{13}C_n F_n + \delta^{13}C_b F_b + \delta^{13}C_t F_t = \delta^{13}C_{measured}$$

$$\delta^{15}N_n F_n + \delta^{15}N_b F_b + \delta^{15}N_t F_t = \delta^{15}N_{measured}$$

where F_n, F_b and F_t represent the fraction of the organic matter with the same composition as the marine (non-bloom), marine (bloom) and terrigenous end-members, respectively, and ($\delta^{13}C_n$, $\delta^{15}N_n$), ($\delta^{13}C_b$, $\delta^{15}N_b$) and ($\delta^{13}C_t$, $\delta^{15}N_t$) are the isotopic compositions of the three end-members.

By this method, we determined that about 80% of the organic matter captured in the sediment trap at station CM4 was marine-derived (F_n+F_b), as was about 60% at stations CM2 and CM3 (Table 3). This finding is consistent with the Johannessen et al. (2003) carbon budget, which indicated that more than half of the particulate organic carbon entering or formed within the Strait of Georgia was marine-derived. To test the observed seasonal difference in the marine-derived organic matter, we compared the summer (April–August) and winter (October–February) average values of the fraction of marine (bloom) organic matter, corrected for the total marine fraction [marine (bloom)/(marine (bloom)+marine (non-bloom); Table 3] at each station using a two-tailed *t*-test. At all three stations and at all three depths at station CM3, the samples collected from April to August contained significantly more marine (bloom; i.e. low $\delta^{15}N$, high $\delta^{13}C$) organic matter than did those collected from October to February (p<0.01). The March and September data were excluded from the statistical analysis, because a transition between "bloom" and "non-bloom" organic matter occurs during those months.

Describing the data with three end-members allows us to distinguish variations in the proportion of terrigenous organic matter from the seasonal variation in the isotopic composition of local phytoplankton.

3.3. Particle transport

The total flux and isotope data suggest that particles settle in the southern Strait (near station CM2) and then move northwards along the bottom, beneath even the 300 m sediment trap, toward stations CM3 and CM4 (Fig. 9). At station CM2, the flux of particles captured by the sediment trap at 150 m was comparable to the mass accumulation rate calculated from a sediment core collected at the same site (Table 2). In contrast, at stations CM3 and CM4, the 150 m flux was only 26% and 17%, respectively, of the mass accumulation rate observed in the corresponding sediment cores. The discrepancy is unlikely to have been caused by inefficient trapping at stations CM3 and CM4 due to strong currents. The current speed at 150 m was less than 22 cm/s 98% of the time at station CM4 (mean=9.5 cm/s; S.D.=5.5 cm/s; n=23298); 93% of the time at station CM3 (mean=11 cm/s; S.D.=6.8 cm/s; n=34161); and 60% of the time at station CM2, where it was generally greater than at the other two stations (mean=21 cm/s; S.D.=14 cm/s; n=27698). It is also unlikely that the higher flux to the bottom sediments was due to increased flocculation with depth, because at station CM3 the flux did not increase uniformly with depth (Table 2): the 300 m trap usually collected the most sediment, but the middle trap (at 225 m) usually collected the least, showing an apparent disconnect between the shallow and deep traps. Freudenthal et al. (2001) explained a similar disconnect between shallow and deep traps and between traps and surface sediments at a site off

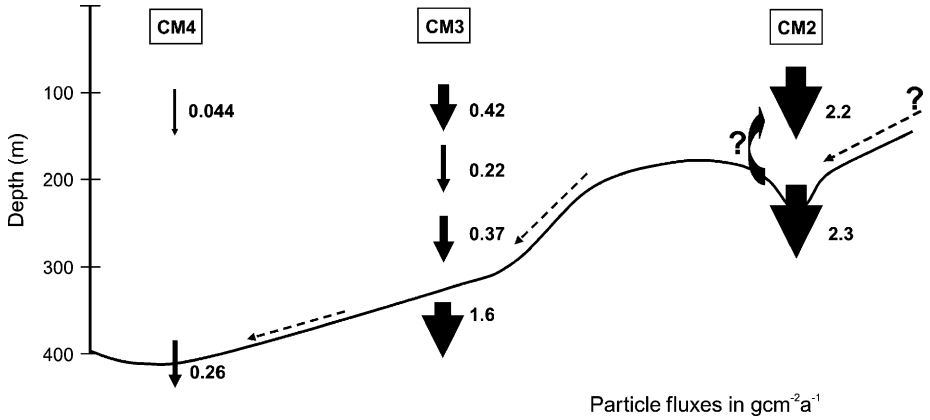

Fig. 9. Cartoon showing annual fluxes and proposed sediment transport pathways to sediment traps and cores. At stations CM3 and CM4 the vertical flux of particles at 150 m (and at 225 and 300 m at station CM3) is much less than the bottom sediment accumulation rate at those stations, while at station CM2, the trap flux and sediment accumulation rate are essentially equal. The total flux and chemical and isotopic composition data suggest that particles settle in the southern strait near station CM2 directly, by resuspension or by horizontal advection from Haro Strait, then travel northwestward along the bottom, toward stations CM3 and CM4. Station CM2 is located within a small, shallow basin, but the surrounding seafloor is shallow enough that particles could move essentially downhill along the bottom from near station CM2 to stations CM3 and CM4.

the Canary Islands as the result of lateral transport, possibly in the nepheloid layer.

At station CM2, to the south of the Fraser River, the flux-weighted, annual average isotopic composition of the organic matter in sinking particles was similar to that measured in the sediment core collected at that site (Fig. 8a; Table 3). At stations CM3 and CM4, however, the isotopic composition of organic matter in the traps was significantly heavier (i.e. more marine) than that in the corresponding cores (Table 3), while the cores at the three sites were very similar isotopically. The difference between the traps and the cores is unlikely to represent reworking in the water column, because the core material was isotopically lighter than that collected in the traps, not heavier, as would be expected from reworking (e.g. Freudenthal et al., 2001). Also, there was no evidence of increasing isotopic depletion with depth in the three traps suspended at 150, 225 and 300 m at station CM3 (Table 3). Advection of largely terrigenous material northward along the bottom of the Strait to stations CM3 and CM4 seems the most plausible explanation.

Direct settling of particles from the Fraser River as a result of estuarine circulation (in which deep, inflowing water transports and deposits particles that have settled from the outflowing surface layer) might account for the large summer flux peak at CM2, but the November/December peak requires another source. This latter peak might have resulted from the entrainment of particles from outside the Strait by episodic deep water renewal (Masson, 2002). If so, the particles probably did not originate on the outer shelf, where almost all the sinking particles are derived from in situ production, because the organic matter at station CM2 was less marine, isotopically, than that at station CM4 in the north-central Strait of Georgia. They may have originated in the Fraser River or the Strait of Georgia and initially settled in Haro Strait, after which the inflow associated with deep-water renewal could have washed them back into the Strait of Georgia and northward to station CM2. Alternatively, the high flux into the sediment trap at station CM2 might represent resuspension of locally settled particles by winter storms. [The CM2 site was shallower (211 m) than the other two sites (349 and 410 m)].

Multibeam bathymetric and high resolution seismic reflection data support the interpretation of large-scale movement of sediments along the bottom of the central Strait: Mosher and Hamilton (1998) have shown hills 20 m high on the bottom of the Strait, near the main mouth of the Fraser River, which are tentatively interpreted as the result of erosion by strong, deep, tidal currents (Mosher and Thomson, 2002). McLaren and Ren (1995) also noted northward sediment movement along the foreslope of the Fraser River delta. This

tendency toward northward advection is further supported by particulate contaminant tracers (Ag and nonylphenol ethoxylates) marking the distribution of the plume emanating from the Iona Island sewage outfall, just offshore to the southwest of the City of Vancouver (Fig. 1; Gordon, 1997; Shang et al., 1999). The northward movement of sediment along the bottom could be driven by the deep, northward return flow in the southern and central Strait caused by the southerly surface outflow of Fraser River water and the resultant estuarine circulation.

4. Conclusions

The sediment trap data presented here demonstrate clear seasonal trends in particle flux and composition. These trends allow a preliminary assessment of particle and organic carbon provenance and pathways through the southern and central Strait of Georgia. The timing of the maximum flux and the high proportion of lithogenic material at all three stations indicate a strong influence from rivers, particularly the Fraser River, while the organic portion of the flux clearly has both terrestrial and marine sources. The large difference between the flux estimated from sediment cores and that estimated from traps at stations CM3 and CM4, together with the stable isotopic composition of organic matter in the cores and traps, suggests that northward currents carry particles along the bottom, toward those two stations. These sediment trap data provide the insight that terrigenous matter is captured in the Strait of Georgia partly by direct vertical flux and partly by a more circuitous route involving near-bottom re-suspension, such that the southern part of the Strait of Georgia accounts for more sediment accumulation than does the inner, northern portion.

The interpretation of the stable isotopic data as the mixing of terrigenous, marine (bloom) and marine (non-bloom) end-members allows the discrimination of two processes that act simultaneously: the mixing of terrigenous and marine-derived organic matter and the variation in seasonal nutrient availability to local phytoplankton. The isotopic seasonal signal in the marine component of the organic carbon flux in the Strait of Georgia mimics the open shelf signal, suggesting that this enclosed sea provides an important extension of the continental shelf where enhanced production of organic carbon is less likely to be exported to the ocean and may, in part, be sequestered through ballasting and rapid sedimentation. A similar "marginal filter" probably operates in other coastal seas that receive significant fluxes of both terrigenous and marine-derived particles, and the isotopic method described here should also be applicable in those cases.

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