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Sediment Pathways in a British Columbia Fjord and Their Relationship with Particle-Associated Contaminants

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ABSTRACT

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About 820 bottom grab samples were collected at regular intervals over Howe Sound, a British Columbia fjord. These were analyzed for their complete grain-size distributions in order to perform a sediment trend analysis. This is a technique whereby net sediment transport patterns are determined by assessing statistically the relative changes in grain-size distributions along selected sample sequences. The analysis also provides an understanding of the behaviour of the sedimentary environment with respect to erosion, deposition or dynamic equilibrium. This information may be used to predict the build-up and/or dispersal of particle-associated contaminants. In Howe Sound, there are two pulp and paper mills which have been sources of dioxins and furans which have led to fisheries closures. In environments where total deposition is occurring (*i.e.*, once deposited, a particle undergoes no further transport) contaminants are concentrated at locations relative to their source. Where sediment in transport becomes so fine (*i.e.*, fine silt and clay) that size-sorting no longer occurs, contaminants have no preferred location for their deposition; rather, contaminated particles have an equal probability of deposition over the whole transport environment. In this study, the spatial distribution of existing contaminant data correlated extremely well with each of the transport environments as determined by the sediment trend analysis.

ADDITIONAL INDEX WORDS: *Grab samples, sediment trend analysis, sediment transport patterns, transport environment.*

INTRODUCTION

Howe Sound is a typical fjord on the west coast of British Columbia (Figure 1). Its natural beauty and close proximity to Vancouver have served to make it a focus for considerable environmental concern, particularly following a fisheries closure in 1988 due to unacceptably high tissue concentrations of dioxins and furans (ENVIRONMENT CANADA, 1992). Such compounds are known to have a high affinity for the organic constituents of abiotic and biotic particles; and, therefore, they become, through physical, chemical and biological processes, inextricably linked to the natural sediment regime (YOUNG *et al.*, 1985). As part of a program to determine the behaviour of contaminants in the Howe Sound ecosystem, Fisheries and Oceans Canada supported a study to determine the role of sediment transport on their distribution in the bottom sediments. The principal purpose of this study, therefore, was to establish the probable sediment transport pathways and to assess those areas in the Sound particularly susceptible to contaminant build-up or dispersal.

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THEORY

To establish the patterns of sediment transport and to describe the nature of the various transport regimes, a sediment trend analysis was undertaken. This technique utilizes the relative changes in grain-size distributions of the bottom sediments. The derived patterns of transport are, in effect, an integration of all processes responsible for the transport and deposition of bottom sediments over the period of time represented by the actual samples. Details of the theory are contained in MCLAREN and BOWLES (1985); however, the following provides a brief summary.

When two sediment samples (D_1 and D_2) are taken sequentially in a known transport direction (*e.g.*, from a river bed where D_1 is the up-current sample and D_2 is the down-current sample), the theory demonstrates that the grain-size distribution of D_2 may become finer (Case B) or coarser (Case C) than D_1. If it becomes finer, the skewness

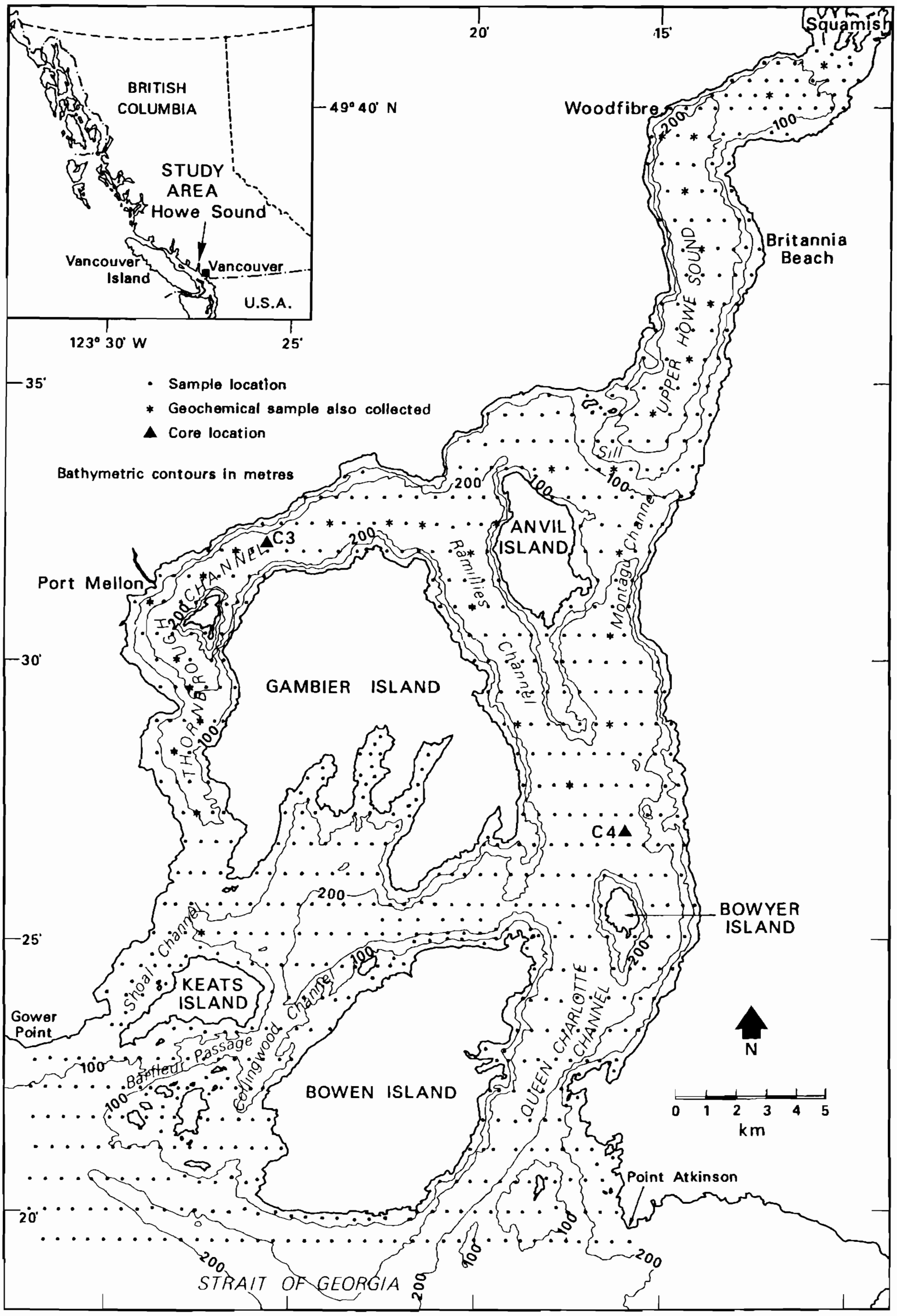


Figure 1. Location map and sample sites.

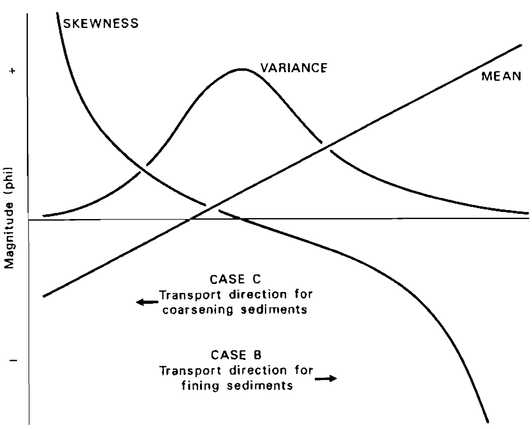


Figure 2. Summary of the changes in grain size measures (phi scale) that may occur in a given direction of transport. The X-axis is distance along the transport path.

of the distribution must become more negative; conversely, if D_2 is coarser than D_1, the skewness must become more positive. The sorting will become better (*i.e.*, the value for variance will become less) for both Case B and C (Figure 2). If the relative changes in the grain-size distributions between D_1 and D_2 are different from the above, transport cannot be assumed to have taken place in the direction defined by the locations of the two samples.

In the event that Case B or Case C transport has been defined by D_1 and D_2, the two distributions can be related to each other by a function X(s) where:

$$X(s) = D_2(s)/D_1(s)$$

and "s" is the grain-size in phi units. X(s) provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular sized grain being eroded and deposited from D_1 to D_2.

Interpretation of the X-Distribution

Empirical examination of X-distributions from a large number of different environments has shown that four basic shapes are most common when compared to the D_1 and D_2 distributions (Figure 3). These are as follows:

(1) Dynamic Equilibrium (Figure 3a): The shape of the X-distribution closely resembles the

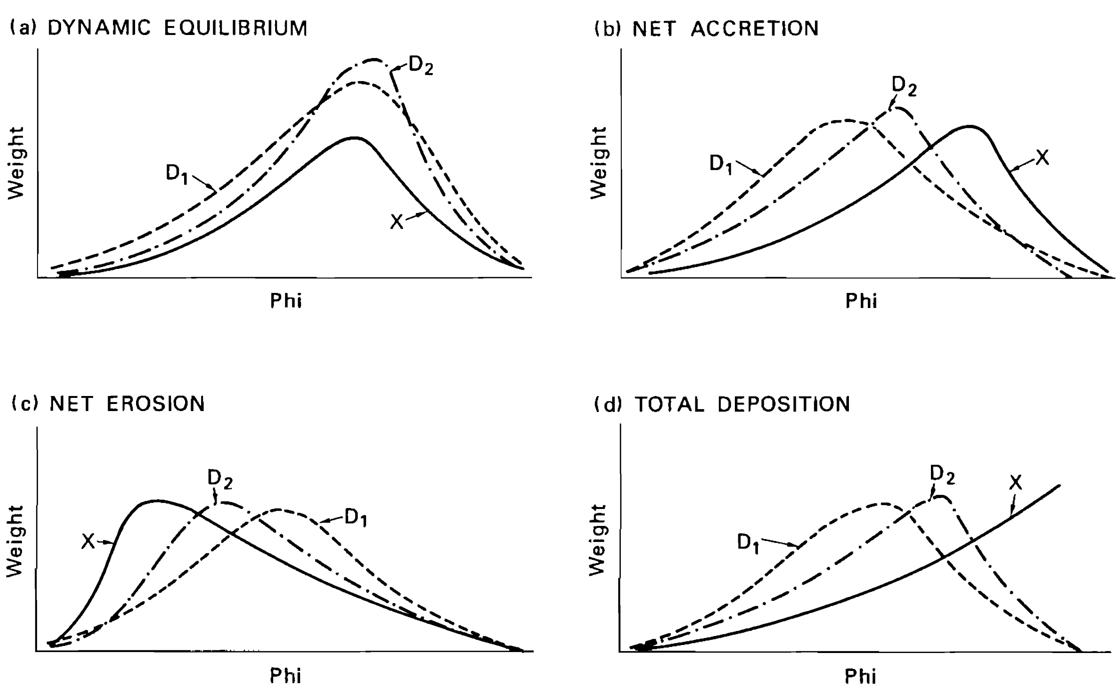


Figure 3. Summary of the interpretations given to the shapes of X-distributions relative to the D_1 and D_2 distributions.

D_1 and D_2 distributions. The relative probability of grains being transported, therefore, is a similar distribution to the actual deposits. This suggests that for every probability of finding a particular grain in the deposit, there is an equal probability that it will be transported and redeposited (*i.e.*, there is a grain-by-grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium.

(2) Net Accretion (Figure 3b): The shapes of the three distributions are similar, but the mode of X is finer than the modes of both D_1 and D_2. Sediment must fine in the transport direction; however, more fine grains are deposited along the transport path than are eroded with the result that the bed, though mobile, is accreting.

(3) Net Erosion (Figure 3c): Again the shapes of the three distributions are similar, but the mode of X is coarser than the D_1 and D_2 modes. Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing net erosion.

(4) Total Deposition (Figure 3d): Regardless of the shapes of D_1 and D_2, the X-distribution more or less increases monotonically over the complete size range of the deposits. Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a "rain" of sediment that fines with distance from source. Once deposited, there is no further transport.

Interpretation of a Trend

In reality, progressive changes in grain-size distributions as shown in Figure 2 are seldom observed in a sequence of samples, even when the transport direction is clearly known. This is due to complicating factors such as variation in the grain-size distributions of source materials, local and temporal variability in the X(s) function, and a variety of sediment sampling difficulties (*i.e.*, sample does not adequately describe the deposit; it's taken too deeply; not deep enough, *etc.*). McLaren (1981) discusses sampling criteria in more detail.

Initially, however, a trend may be easily determined using a statistical approach whereby, instead of searching for "perfect" changes contained within a sequence of samples, all possible pairs contained in the sequence are assessed for possible transport direction. When one of the trends (Case B or Case C) exceeds random probability within the sample sequence (at least 9 samples are required in a sequence to be statistically acceptable), the direction of transport can be inferred and the X(s) function calculated. The precise statistical technique is described in McLaren and Bowles (1985) and discussed further by Gao and Collins (1991).

Despite the initial use of a statistical test, various other qualitative assessments must be made in the final acceptance or rejection of a trend. Included is an evaluation of R^2, a multiple correlation coefficient defining the relationship among the mean, sorting and skewness of each sample contained in the sequence. If, for example, a given sample sequence follows a transport path perfectly, the three grain-size descriptors will contain a relationship as defined in Figure 2. R^2 will, therefore, approach 1.0 (*i.e.*, the sediments are perfectly "transport-related"). On the other hand, a low R^2 may occur even when a trend appears statistically acceptable for the following reasons: (i) sediments on a presumed transport path are, in reality, from different facies, and valid trend statistics occurred accidently; (ii) the sediments are from a single facies, but the sequence chosen deviates from the actual transport path, and (iii) extraneous sediments have been introduced into the natural transport regime, as in the case of dredged material disposal. R^2, therefore, is assessed qualitatively, and when low, statistically acceptable trends must be treated with caution.

To undertake a sediment trend analysis, usually a regular grid of samples is required. Each sample is analysed for its complete grain-size distribution which is entered into a micro-computer equipped with appropriate software to calculate statistically acceptable trends for all sample sequences. The corresponding X(s) functions are calculated for those sequences exhibiting acceptable transport trends. Most importantly, a final interpretation of the transport pathways is accepted only when the patterns of transport form a "coherent whole" over the entire area of sampling (*i.e.*, all or nearly all of the samples are contained in acceptable sequences, and the results from different sequences mutually support each other).

PHYSICAL SETTING

The fjord of Howe Sound originates at the Squamish delta, about 40 km inland from the Strait of Georgia. Exhibiting a typical U-shaped submarine valley, its width is about 3.5 km in the northern portion. Water depths increase rapidly from Squamish to about 220 m near Woodfibre (Figure 1), and then more gradually to nearly 300 m at the base of a sill 17 km to the south. The water depth over the sill is in places less than 50 m; it is composed of morainic materials and marks the maximum ice advance of the Fraser glaciation (11,300 yrs BP) (MATHEWS *et al.*, 1970). South of the sill, the fjord divides into a number of channels with widths of up to 6 km and each with an average depth of 230 m.

The Squamish River, which drains 3,600 km^2 of the southern coast mountains, yields about 1.5 $\times 10^6$ m^3 a^{-1} of sediment into Howe Sound and appears to be the dominant influence on the circulation of surface water in the Sound (HICKIN, 1989). The present Squamish delta is prograding down-fjord at an average rate of 3.86 m a^{-1}. In the Sound itself, the bottom is covered by a layer of 50–150 m of Holocene sediments that overlie thick deposits of Pleistocene sediment (SYVITSKI and MACDONALD, 1982). According to HICKIN (1989), the rate of sedimentation decreases exponentially down the fjord with an average annual accumulation of 4.0 mm a^{-1} near Britannia Beach and 0.20 mm a^{-1} at the foot of the sill. These rates have been approximated by STRONACH *et al.* (1992) in a modeling study which combined a 3-dimensional hydrodynamic model with a simulated depositional model.

In addition to the transport and deposition of sediments by the "normal" circulation of fjord waters, considerable transfer of materials is achieved by catastrophic mass movements down the Squamish delta front and sides of the Sound. PRIOR and BORNHOLD (1984) using sub-bottom profiling and side scan sonar surveys have shown a complex bottom morphology consisting of numerous elongate chutes which incise the delta slope to water depths of 200 m. At their downslope ends, these chutes terminate in debris fans and associated features such as closely spaced arcuate scarps and large allochthonous sediment blocks that have moved across the fjord floor as a result of load-related sliding.

The oceanography of the Sound has received much attention and thorough literature reviews are contained in SYVITSKI and MACDONALD (1982) and HICKIN (1989). The fjord is contained in a macrotidal environment (range 5.5 m); however, tidal oscillations contribute little to residual currents and their influence decreases with depth (PICKARD, 1961). More important in the generation of residual flows are the freshwater discharges of the Squamish River at the north end of the Sound and the Fraser River, the north arm of which is located about 10 km south of the mouth of Howe Sound. The latter is given considerable importance as a sediment source for deposits throughout the Sound as far north as Anvil Island and the sill (SYVITSKI and MACDONALD, 1982; HAMILTON, 1992). Also significant in producing residual currents are katabatic winds which are generated over hinterland icefields and result in strong up-inlet and stronger down-inlet stresses causing both short-term residual velocities in the surface waters and deep water exchanges at the sill (BUCKLEY, 1977).

Current measurements show that velocities throughout the water column are usually lower than 0.8 m sec^{-1}. BUCKLEY (1977) and BUCKLEY and POND (1976) described a surface-layer outflow and a return flow in the waters immediately below. A mean down-inlet flow was observed in the deeper waters below 130 m in the waters north of the sill.

At present, Howe Sound supports two pulp and paper mills at Port Mellon and Woodfibre as well as a chlor-alkali plant at Squamish. The latter was a source for mercury in the sediments, the distribution of which is described in THOMPSON *et al.* (1980). Much of the fjord bottom in the vicinity of the two pulp mills is covered with bark mulch, and effluent from the manufacture of pulp and paper (as a result of using chlorine) is considered to be a source of dioxins and furans.

FIELD METHODS AND DATA BASE

Sample Collection

The findings described in this paper are the result of three separate phases of a project designed to complete a sediment trend analysis for the whole of Howe Sound. A separate report was prepared at the end of each phase (GEOSEA CONSULTING (CANADA) LTD., 1990, 1991, 1992). In the first analysis, samples were collected with a Van Veen grab between January 4 and January 12, 1990, and covered the area from Squamish, south to the latitude of Port Mellon and Anvil Island. The sampling strategy was based on a grid with spacing of 500 m across the fjord width and 1 km spacing down the channels (Figure 1). Positioning was achieved using radar bearings.

A sub-sample of the top 10–15 cm of each grab was collected for grain-size determination. In addition, a selection of the grabs was further subsampled for future chemical analyses (Figure 1).

The second phase continued from the first with an identical sampling strategy and extended the coverage to the northern tip of Bowen Island. The samples were collected between December 3 and December 17, 1990. The remainder of the Sound was completed in Phase III between November 17 and November 22, 1991. In all, a total of about 820 samples were obtained for the trend analysis.

Grain-Size Analysis

The samples were all analysed using a standardized method developed by GeoSea Consulting. This combines measurements on a Malvern 2600L laser particle sizer with data obtained from dry sieving the gravel and coarse sand fractions (−2.0 phi to −0.5 phi) where necessary. All samples were well mixed prior to analysis in order to obtain a representative sub-sample. About 5 per cent of the samples were re-analyzed to ensure reproducibility in accordance to laboratory procedures defined by the U.S. Environmental Protection Agency.

The Malvern instrument employs lenses of different focal lengths to look at portions of the total range of grain sizes. Frequently, two measurements were required: one to encompass the sand fraction and the other the silts and clays. The separate distributions and sieve data were then "merged" together using an algorithm to reproportion the weight percents into a single, complete distribution. This was accomplished with software developed by GeoSea Consulting and the merged data provided the data base used in the sediment trend analysis.

PRESENT PATTERNS OF SEDIMENTATION

A sediment trend analysis was performed separately for each of the three Phases of the study. The findings of each were integrated and found to be compatible with the results of the preceding Phase, thus providing mutual support for the complete interpretation. The sediment trend software, proprietary to GeoSea, allows total freedom to "explore" the data for all possible transport pathways, the final interpretation being acceptable according to the above discussion. In all, about 80 sample sequences were selected to define the transport pathways in Howe Sound. Maps of the sample lines and the complete sediment trend statistics are provided in the individual reports and can be made available on request (GEOSEA CONSULTING, 1990, 1991, 1992), but for the sake of brevity, are not included here. Figure 4 illustrates the derived transport pathways, and the findings of the sediment trend analysis are discussed according to specific regions as follows:

(1) Upper Howe Sound

The lines of samples used in the trend analysis for this region originated at the Squamish Delta and terminated at the base of the sill. With the exception of the sample sequences immediately adjacent to the fjord sides, all the lines produced exceptionally good statistics showing Case B transport (*i.e.*, sediment fining) in a down-fjord direction. R^2 values for these lines were also exceptionally high (0.86 ± 0.10; Table 1) and the corresponding X-distributions were each indicative of total deposition (Figure 5). Trends close to the fjord sides were weakest (no trend could be obtained for the samples closest to the east wall) probably due to local sediment sources derived from the steep surrounding walls and slope instability.

(2) Ramilles Channel

Ten sample sequences were used to determine the transport trends from the base of the sill through Ramilles Channel to the northern part of Queen Charlotte Channel. The direction for all the lines was south, although there appears to be some indication that transport is diverted in and out of the channel separating Gambier Island from Bowen Island (Figure 4). The distinguishing feature of these lines compared to the Upper Howe Sound lines is that nearly all the trends were Case C, although as seen in Figure 6, there is almost negligible difference between the D_1 and D_2 distributions. Furthermore, the derived X-distribution is essentially horizontal (Figure 6), a shape that is undefined according to Figure 3. The average R^2 value for this region is significantly lower than that of Upper Howe Sound (0.69 ± 0.27; Table 1).

(3) Montagu Channel

Similar to Ramilles Channel, the sample sequences for this area also originate at the base of the sill and continue southwards as far as Bowyer Island. The trends are identical to those in Ramillies Channel, the statistics showing Case C transport to the south as well as horizontal X-distributions. The average R^2, however, is considerably higher with values much the same as Upper Howe Sound (0.88 ± 0.06; Table 1).

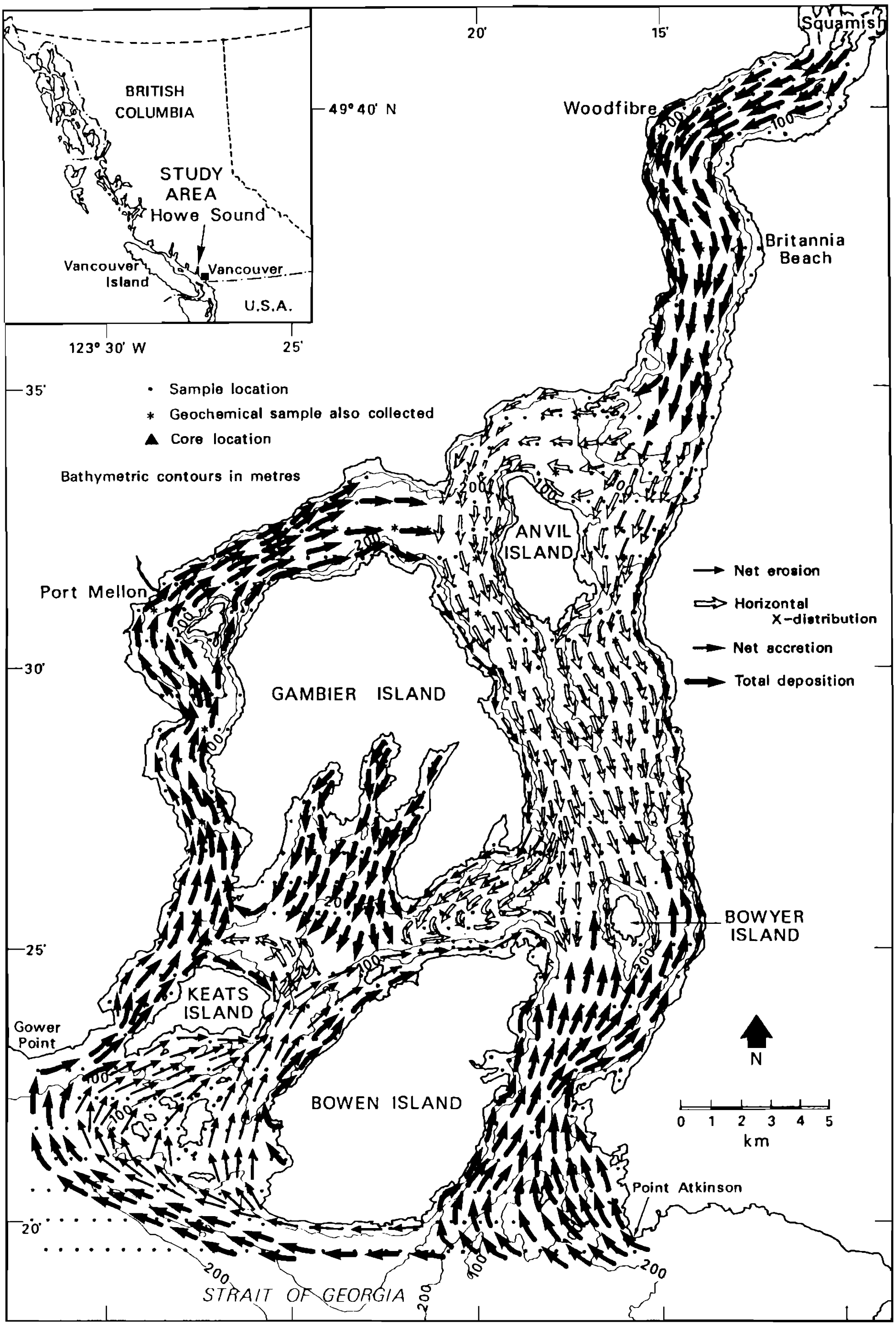


Figure 4. Net sediment transport pathways.

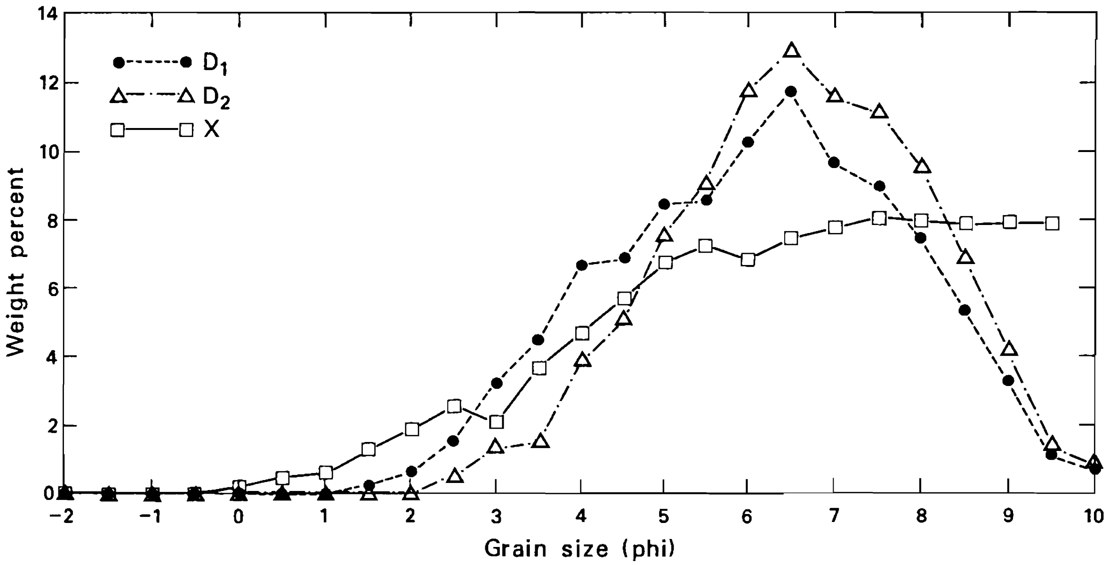


Figure 5. Typical D_1, D_2 and X-distributions for Upper Howe Sound. The X-distribution signifies total deposition (*i.e.*, once deposited, a particle undergoes no further transport). Compare with Figure 3D.

(4) Southern Gambier Island

The southern end of Gambier Island is composed of three bays that open into a single large bay (unnamed). A small river enters each of the small bays. Excellent trends were determined for lines of samples originating near the river mouths and entering the large bay. All lines showed Case B transport indicative of total deposition. Similar to Upper Howe Sound and Montagu Channel, the average R^2 was extremely high (0.88 ± 0.07; Table 1).

(5) Queen Charlotte Channel

These lines originate in the Strait of Georgia near Point Atkinson immediately to the southeast of Howe Sound. Although the derived pathways are, in every case, northwards from the Strait into Queen Charlotte Sound, they appear to be strongly influenced by a westerly transport regime crossing the mouth of the Sound. All the transport paths inside Queen Charlotte Sound could be tied into this westerly transport regime which, unfortunately, is based only on one line of samples. This may explain the rather low R^2 values achieved for these lines (0.72 ± 0.07; Table 1). Possibly an extension of the sample grid farther into the Strait of Georgia could define more accurate transport paths resulting in higher R^2 values. Each of the Queen Charlotte Sound lines produced X-distributions indicative of total deposition (Figure 7). They terminate in the vicinity of Bowyer Island

Table 1. *Summary of the sediment transport environments in Howe Sound.*

	Environment	No. of Sample Lines	Mean R^2 Values	Interpretation of X-Distribution
1	Upper Howe Sound	7	0.86 ± 0.10	Total deposition (Figure 5)
2	Ramillies Channel	10	0.69 ± 0.27	Horizontal (Figure 6)
3	Montagu Channel	8	0.88 ± 0.06	Horizontal
4	Southern Gambier Island	10	0.88 ± 0.07	Total deposition
5	Queen Charlotte Channel	16	0.72 ± 0.07	Total deposition (Figure 7)
6	Strait of Georgia	3	0.75 ± 0.16	Total deposition
7	Collingwood/Barfleur	15	0.91 ± 0.04	Slight net erosion (Figure 8)
8	Shoal and Thornbrough	8	0.40 ± 0.19	Total deposition (Figure 9)

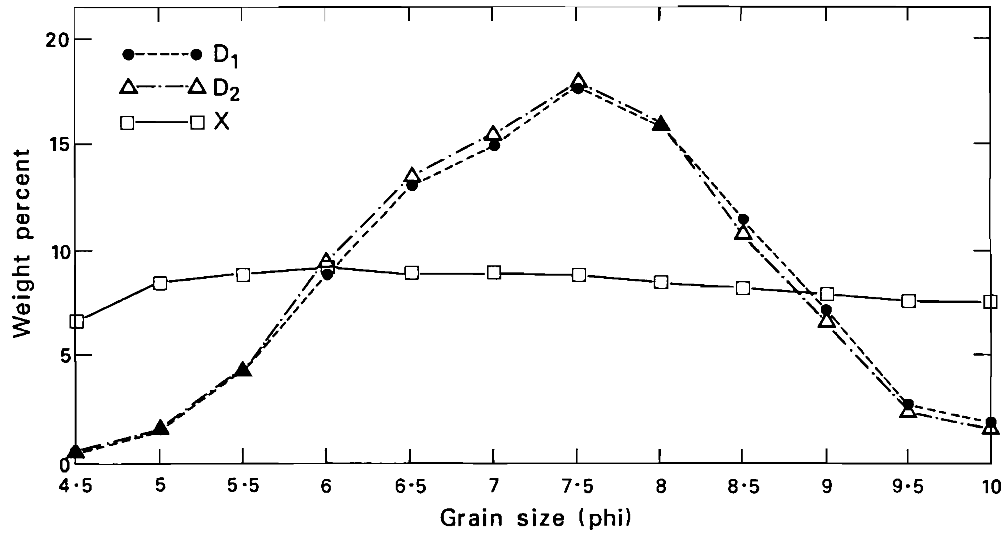


Figure 6. D_1, D_2 and X-distributions for Ramillies Channel sediments illustrating the undefined horizontal X-distribution.

where they meet the southward trending lines of Ramillies and Montagu Channels.

(6) Strait of Georgia

As in the Queen Charlotte sample lines, these lines originate near Point Atkinson and define the previously discussed westward transport regime that appears to cross the mouth of Howe Sound. Opposite the southwest end of Bowen Island, the pathways curve northwards towards Gower Point on the mainland coast. Each of the lines indicates total deposition and, as in Queen Charlotte Channel, R^2 values are not particularly high (0.75 ± 0.16; Table 1).

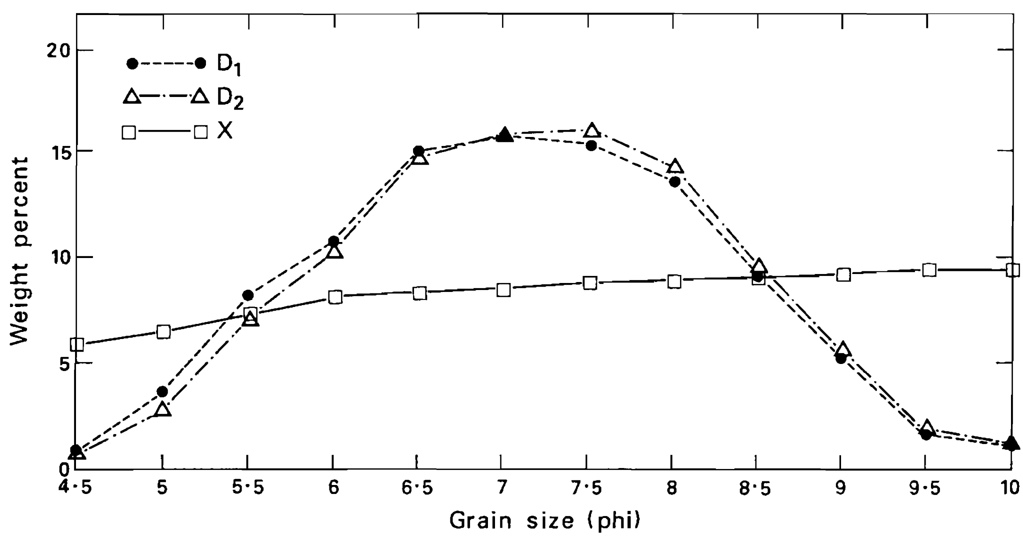


Figure 7. D_1, D_2 and X-distributions for Queen Charlotte Channel samples suggesting total deposition of sediments is occurring in this area.

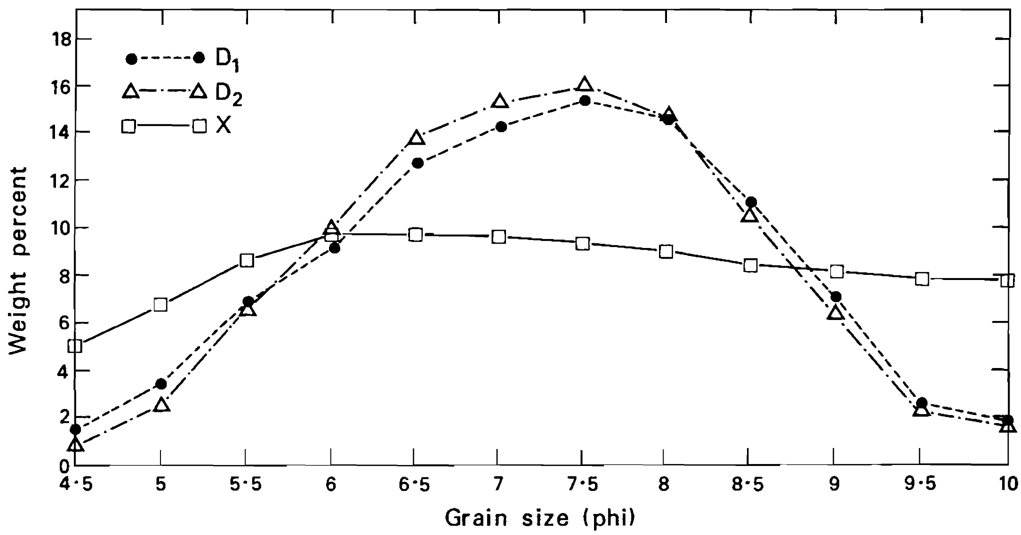


Figure 8. D_1, D_2 and X-distributions for samples in the Collingwood Channel and Barfleur Passage suggesting net erosion of these sediments (compare with Figure 3C).

(7) Collingwood Channel/Barfleur Passage

The majority of these lines originate along the nearshore of the south coast of Bowen Island and trend westwards and northwards into Howe Sound. The trend statistics indicate Case C transport and the X-distributions suggest that slight erosion is occurring through Collingwood Channel, Barfleur Passage and through the channels that pass among the group of islands that lie between Bowen and Keats Islands (Figure 8). These lines meet the southward trends defined by the Southern Gambier Island regime and are deflected east and west in the unnamed channel between

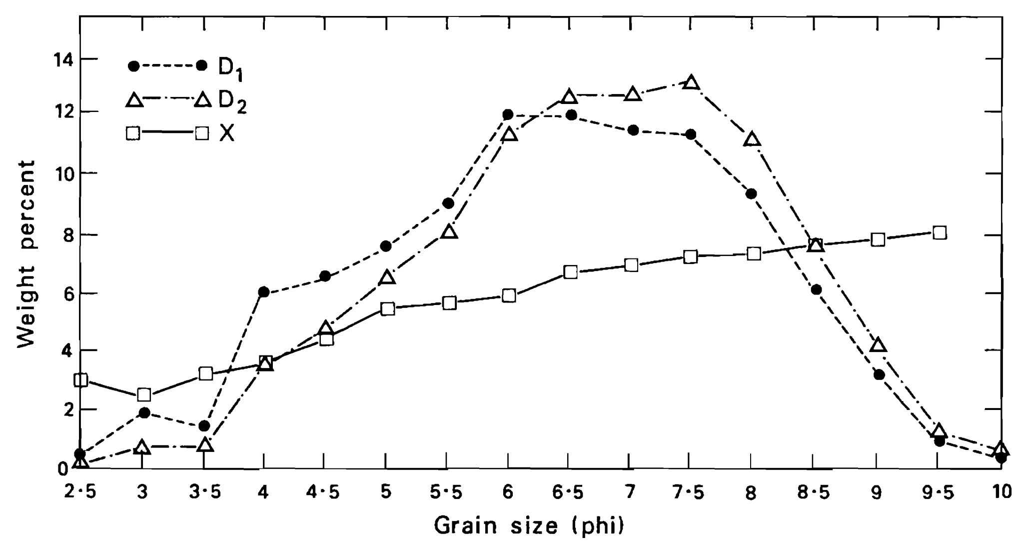


Figure 9. D_1, D_2 and X-distributions for samples in Shoal and Thornbrough Channels indicating total deposition of sediments (compare with Figure 3D).

the south coast of Gambier Island and the north coasts of Keats and Bowen Islands.

Two sample sequences adjacent to the west coast of Bowen Island originate from creeks flowing into Collingwood Channel (Explosives and Malkin Creeks). These lines are exceptional in that the X-distributions indicate total deposition rather than erosion. Several of the lines through Collingwood Channel terminate in the basin between Gambier and Keats Islands and their X-distributions approach a horizontal configuration. Unlike the Queen Charlotte Channel and Strait of Georgia lines, the R^2 values for these trends are very high (0.91 ± 0.04; Table 1).

(8) Shoal and Thornbrough Channels

Transport in this area originates in the Strait of Georgia near Gower Point and passes northwards through both Shoal and Thornbrough Channels to join with Ramillies Channel. Nearly all the sample sequences produced X-distributions indicative of total deposition (Figure 9). The R^2 values, however, were the lowest found in the complete study area (0.40 ± 0.07; Table 1).

Discussion

The derived transport patterns in Upper Howe Sound (Figure 4) agree well with known surface currents which are dominated by the outflow of the Squamish River (BUCKLEY, 1977) as well as with currents in deep water (> 150 m) (BELL, 1975). Two minor discrepancies exist: surface drogue studies by BUCKLEY (1977) show the presence of a clockwise gyre between Squamish and Woodfibre and a counterclockwise gyre in the vicinity of Britannia Beach. Neither gyre could be detected in the trend analysis suggesting that outflowing bottom currents may be negating the effects of the surface circulation at these locations.

Down-fjord transport appears to dominate the eastern regions of Howe Sound at least as far as the northern end of Bowen Island. However, the X-distribution which so clearly defines an environment of total deposition between Squamish and the sill changes in Ramillies and Montagu Channels. In the latter environments, the X-distributions are essentially horizontal which have not been previously observed. An explanation for such a distribution may be that remaining particles in transport south of the sill are too small to be deposited on the basis of size-sorting. In other words, there is now an equal probability of all sizes being deposited regardless of particle size. This concept is partially substantiated by the fact that the mean modal size for the sediments found in Ramillies and Montagu Channels is a full phi size finer than for the sediments north of the sill (7.5 phi compared to 6.5 phi respectively; see Figures 5 and 6 for comparison). Only along the sides of the fjord where there is an input of larger sized materials can the more typical X-distributions be observed (Figure 4).

With the exception of the obviously local depositional transport regime defined for Southern Gambier Island, the remaining trends are all flood dominated. On the east side of Howe Sound, the meeting of the two opposing regimes is roughly at the latitude of Bowyer Island, and coincides with the area of mixing between Fraser and Squamish River waters as defined by water densities (STRONACH *et al.*, 1992). Thus, it appears likely that sediments entering Queen Charlotte Channel from the south are related to Fraser River sediments.

It is important to note that, while there is no major change in sediment type between the facies found in Queen Charlotte Channel and that found in Ramillies or Montagu Channels (*i.e.*, they are all unimodal muds, although the Queen Charlotte Channel samples are, on average, 0.5 phi coarser), there is a significant change in the shape of the X-distributions. Unlike the horizontal distributions discussed earlier, the X-distributions for the sediments coming in from the Strait of Georgia are monotonically increasing indicating that size-sorting is taking place and that total deposition is occurring.

It is probable that the presence of size-sorting is indicative of proximity to source. In Upper Howe Sound, monotonically increasing X-distributions were observed from the mouth of the Squamish to the sill, a distance of 13 km. For a further 15 km south of the sill, as far as Bowyer Island, the sediments have a Squamish River source, but are essentially no longer size-sorted. In Queen Charlotte Channel, the sediments are less than 10 km from the mouth of the North Arm of the Fraser River, a distance that appears to be well within range for size-sorting and, hence, a monotonically increasing X-distribution. The somewhat low R^2 values for the transport regime into Queen Charlotte Channel may be due to the fact that these sediments are, as they progress northwards into Howe Sound, becoming mixed with Squamish River sediment.

On the west side of Bowen Island in Collingwood Channel and Barfleur Passage, transport is clearly flood dominated; however, all the trends are Case C with X-distributions suggesting slight net erosion. Thus, while Fraser River sediments may be transported into the Sound, it is unlikely that they are being deposited in this region. There is some evidence that deposition is occurring in the channel between Keats and Gambier Islands, although assignment of samples in this region to either the South Gambier regime or to the Collingwood Channel/Barfleur Passage sediments was often not particularly clear. More likely, sediments in this region are a mixture from the two transport regimes.

In Shoal and Thornbrough Channels, transport is flood dominated and the sediments are undergoing total deposition. Compared to Queen Charlotte Channel, this area is considerably farther from the Fraser River (Shoal Channel is 19 km from the North Arm), and thus it seems unlikely that the Fraser is responsible for these sediments.

In this respect, it is anomalous that total deposition is occurring in Thornbrough Channel; rather, it would be expected to see horizontal X-distributions for this region, a finding more in keeping with a distant source such as the Fraser River. Possibly Shoal and Thornbrough Channels are receiving a significant sediment load from the surrounding land. Compared to the other channels that make up Howe Sound, these channels are narrow, and the creeks on the western side of this portion of the Sound are both larger and more numerous than elsewhere.

The flood-dominated transport through Shoal and Thornbrough Channels all the way to the north side of Gambier Island is a finding contrary to the patterns of transport determined by SYVITSKI and MACDONALD (1982). Their interpretation, based on about 8 bottom samples, shows that concentrations of mica, nickle and copper protrude from the north into Thornbrough Channel. Possibly the mineralogical content of the sediments is more related to grain size than to transport direction. Nevertheless, the trends obtained in Thornbrough Channel contain exceptionally low R^2 values (Table 1) which is attributed both to the nearby influence of numerous creeks and to a dumpsite adjacent to Port Mellon. It is interesting to note that R^2 values for Ramillies Channel are also low compared to the other environments (Table 1). This may be explained by an input of Thornbrough Channel sediments mixing with the Ramillies Channel transport regime. The latter is dominated by the Squamish River and even a small input from Thornbrough Channel would have the effect of introducing an extraneous sediment, and thus lowering the R^2 value. The sediments on the Montagu Channel side have no such mixture of sediments; hence, the mean R^2 value is significantly higher (Table 1).

IMPLICATIONS TO CONTAMINANT TRANSPORT

Introduction

The relationships between contaminants and the sediment transport pathways were first determined in a study by MCLAREN and LITTLE (1987). Similar findings have been observed in a variety of environments including Liverpool Bay and the Bristol Channel in the U.K., Sullom Voe in the Shetland Islands, and the Fraser Delta on the west coast of Canada. These may be summarized as follows:

(1) Given a greater surface area and more sites available for adsorption, contaminants have a greater association with fine sediment (silt and clay) than with coarse sediment (sand).

(2) Sediments that are in dynamic equilibrium (Figure 3a) show no relationship between contaminant loadings and distance along the transport path.

(3) In environments undergoing net accretion (Figure 3b), there is a general linear increase of contaminant loadings along the transport path. Because sediment transport is the cause of contaminant concentration, a specific pollution source cannot usually be assigned.

(4) Contaminant loadings decrease rapidly along an eroding transport path (Figure 3c).

(5) The highest contaminant loadings are found in environments of total deposition (Figure 3d) and these generally can be associated with a specific source.

According to the above concepts, contaminant levels should be highest in environments of total deposition (Table 1). In Upper Howe Sound, for example, data for mercury in the sediments (associated with the chlor-alkali plant at Squamish) showed the highest concentrations in the centre of the fjord about 2 km south of Woodfiber. Beyond this point concentrations decreased, and a repeat survey four years later showed no change in concentrations (THOMPSON *et al.*, 1980). Such a finding is to be expected in an environment of total deposition where contaminated particles,

Table 2. *Mean values (pg/g ⁻¹) of dioxins and furans in each of the Howe Sound environments (corrected for sedimentation rate).*

	Upper Howe Sound N = 9		Ramillies Channel N = 6		Montagu Channel N = 4		Thornbrough Channel N = 12	
	Mean	Coeff. of Var.	Mean	Coeff. of Var.	Mean	Coeff. of Var.	Mean	Coeff. of Var.
Total T4CDD	8.33	2.83	2.22	1.42	0.22	1.73	11.84	0.60
Total P5CDD	144.84	1.71	27.69	0.42	5.29*	1.00	51.67	0.41
1,2,3,6,7,8-H6CDD	857.67	1.33	71.11	0.26	23.92*	0.34	132.25	0.55
1,2,3,7,8,9-H6CDD	363.13	1.32	40.30	0.56	10.35*	0.36	60.30	0.48
Total H6CDD	5,602.67	1.36	452.40	0.28	149.50*	0.34	833.37	0.52
1,2,3,4,6,7,8-H7CDD	567.89	0.94	46.02	0.21	20.82*	0.48	70.07	1.09
Total H7CDD	1,007.33	0.95	87.49	0.23	37.84*	0.44	132.37	1.04
O8CDD	1,861.42	0.95	209.30	0.35	89.70*	0.43	323.92	2.02
Total PCDD	8,624.60	1.12	779.10	0.10	282.54*	0.37	1,353.16	0.71
2,3,7,8-T4CDF	898.56	1.14	40.56	0.36	13.80*	0.27	85.60	0.39
Total T4CDF	1,411.87	1.23	59.28	0.42	19.55*	0.29	134.93	0.38
Total H6CDF	330.68	1.86	31.33	0.23	15.41*	0.34	38.87	1.29
1,2,3,4,6,7,8-H7CDF	343.04	1.51	34.19	0.28	17.14*	0.32	44.58	1.64
Total H7CDF	848.73	1.57	79.43	0.32	36.00*	0.26	114.20	1.89
O8CDF	172.02	1.35	19.89	0.42	9.66*	0.34	28.44	2.05
Total PCDF	2,864.03	1.12	196.59	0.18	82.79*	0.26	328.94	1.07
Total PCDD & PCDF	11,488.63	1.09	975.69	0.11	365.33*	0.33	1,682.10	0.77
Mean coefficient of variation		1.37		0.36		0.47		0.99

* Mean values in Montagu Channel are significantly lower than the values in Ramillies Channel (0.01 level)
T4CDD = Tetrachlorodibenzodioxin, P5CDD = Pentachlorodibenzodioxin, H6CDD = Hexachlorodibenzodioxin, H7CDD = Heptachlorodibenzodioxin, O8CDD = Octachlorodibenzodioxin, T4CDF = Tetrachlorodibenzofuran, H6CDF = Hexachlorodibenzofuran, H7CDF = Heptachlorodibenzofuran, O8CDF = Octachlorodibenzofuran, PCDD = Polychlorinated Dibenzodioxin, PCDF = Polychlorinated Dibenzofuran

once deposited, undergo no further transport. DRYSDALE and PEDERSEN (1991) reported similar observations for heavy metal enrichments associated with mine tailings disposal in the vicinity of Britannia Beach. Here, high levels of metals were located in the sediments immediately south of the source in a direction defined by the transport pathways.

In two of the transport environments (Ramillies and Montagu Channels), the derived X-distributions were horizontal. If, as discussed earlier, such a distribution represents no further size-sorting of the sediments in transport, it is unlikely that contaminants would have any favoured location for their deposition. Rather, particles containing contaminants would be deposited with equal probability throughout the area.

In this study, dioxin and furan contaminants were obtained from the sediments of only four of the eight transport environments defined in Table 1 (Table 2). The complete analytical procedures are described in CRETNEY *et al.* (1992) and in MACDONALD *et al.* (1992). Other contaminant data sources, notably from TRUDEL (1991) and those contained in consultants reports (HATFIELD CONSULTANTS LTD., 1991) were also examined in detail. These studies contained less data than those presented here, and are therefore not reported; however they provided further support for the findings contained in this study.

The Influence of Depositional Rate

The raw contaminant data determined for the top centimetre of each of the grab samples illustrated in Figure 1 represented a concentration per dry weight of sample (pg g^{-1}). Such a value takes no account of the rate of deposition. For example, contaminated particles deposited in an area of slow accumulation would yield a high concentration compared to the same number of contaminated particles deposited in an area of high accumulation. In other words, dilution with non-contaminated particles will appear to decrease the measured amounts of contaminant.

For this reason, an attempt was made to "normalize" each raw value by multiplying it with a depositional rate to provide a flux. In Upper Howe Sound, a rate for each of the 9 samples was taken from the numerical model presented in STRONACH *et al.* (1992). This model considers only the effects of the Squamish River as a sediment source, but the rates calculated between the river outflow and the sill agree well with those calculated by HICKIN (1989) and are reasonably confirmed by mercury data from a core reported in THOMPSON *et al.* (1980). These rates range from 76 mm a^{-1} near the mouth of the Squamish River to about 1.0 mm a^{-1} in the vicinity of the sill.

South of the sill in Ramillies and Montagu Channels, the remaining particles derived from the Squamish River are no longer deposited on the basis of size-sorting. Thus, it is reasonable to assume a more or less equal rate of deposition for both Channels. This was determined from a ^{210}Pb profile of a core (C4, Figure 1) located north of Bowyer Island (0.78 mm a^{-1}; MACDONALD *et al.*, 1992). Far more problematical is the rate chosen for Thornbrough Channel, an environment similar to Upper Howe Sound where total deposition of sediments is occurring. Only one value (0.46 mm a^{-1}) derived from a core (C3, Figure 1) is presently available (also calculated by ^{210}Pb dating; MACDONALD *et al.*, 1992), and this was used for each of the 12 Thornbrough Channel samples.

Discussion

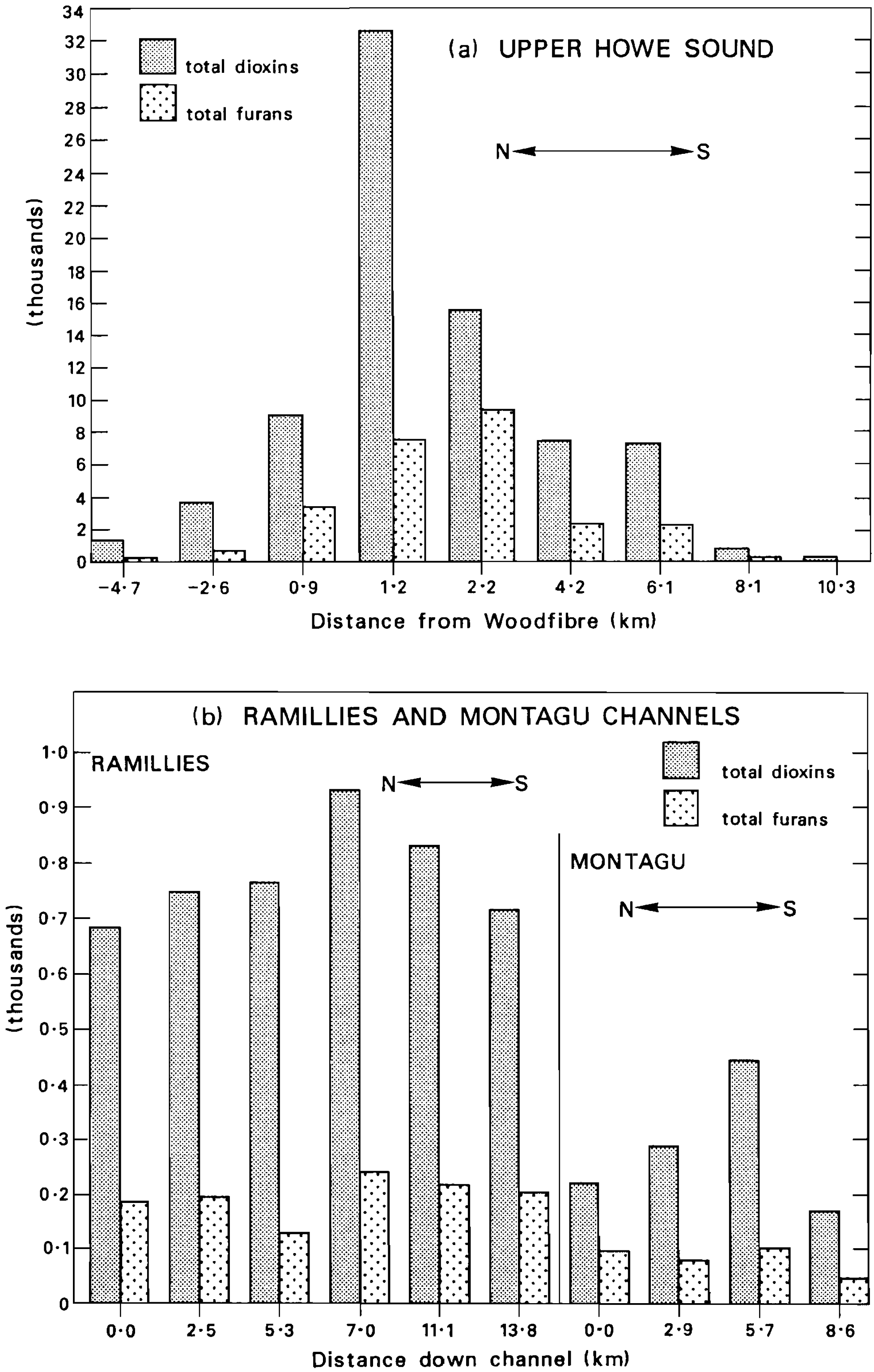
The mean contaminant values shown in Table 2 contain several features supporting the findings of the sediment trend analysis. Both Upper Howe Sound and Thornbrough Channels have high coefficient of variation values compared to Ramillies and Montagu Channels. Such a difference serves to verify the significance of contaminant behaviour in an environment of total deposition (*i.e.*, a monotonically increasing X-function; Figure 3d) compared to an environment where the X-function is horizontal. In the latter, particles have an equal probability of deposition over the defined area with the result that contamination values derived from each sample do not have a wide variability. On the other hand, Upper Howe Sound and Thornbrough Channel are characterized by a size-sorting of sediment with the result that contaminated particles have preferred locations for their deposition. Consequently, variability among contaminant loadings will be larger.

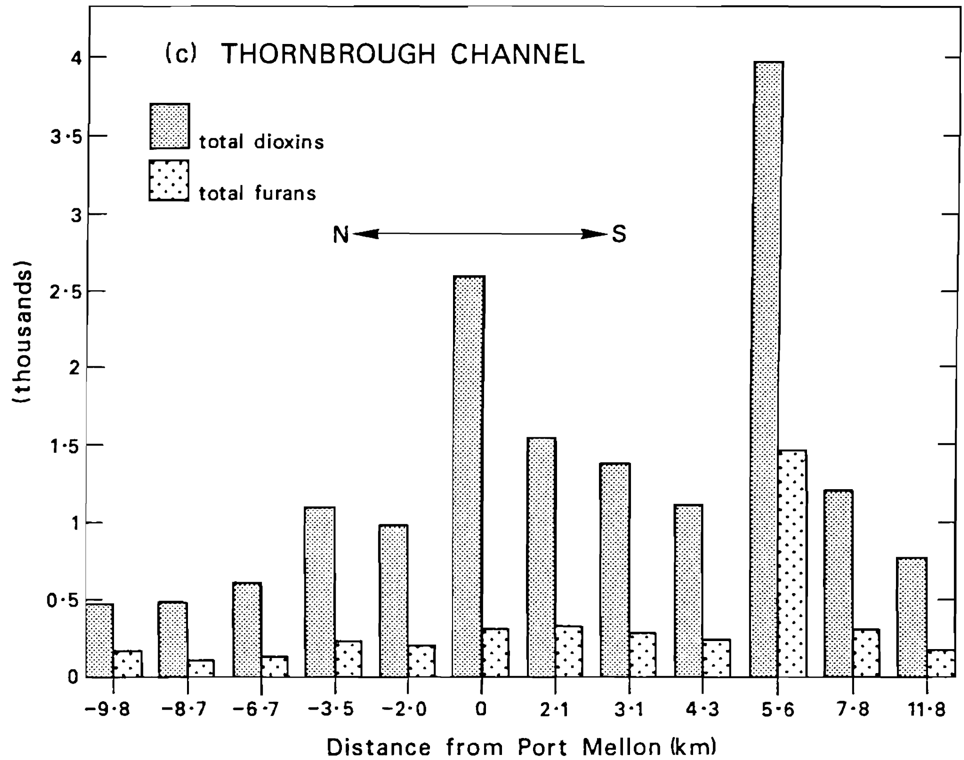
These differences in the variability of contaminant concentrations are more clearly seen in Figure 10. For Upper Howe Sound, the highest values are located 1.2 km south of the pulp and paper mill beyond which values decrease steadily to the sill (Figure 10a). The southward displacement of the peak correlates with the derived direction of transport and reflects the influence of the Squamish River. South of the sill in Ramillies and Montagu Channels, however, the concentrations of dioxins and furans in the sediments have comparatively little variation (Figure 10b).

Similar to the Upper Howe Sound environment, Thornbrough Channel also displays a peak contaminant loading with concentrations generally falling off on either side (Figure 10c). By analogy to Upper Howe Sound, it would follow that peak concentrations should be found north and east of the Port Mellon pulp and paper plant (*i.e.*, in the direction of net sediment transport). Instead, the peak value is at the pulp mill and, somewhat contrary to expectations, it appears that concentrations are somewhat higher to the south compared to the north.

One sample, 5.6 km south of the plant, shows anomalously high concentrations. In this sample, the octachloro- and heptachloro- dibenzodioxin and dibenzofuran concentrations are more than ten-fold greater than those found in the other Thornbrough Channel samples. On the other hand, the tetrachloro- and pentachloro- substituted congener concentrations are about the same. The pattern of the heptachloro- and octachloro- substituted congeners is consistent with atmospherically-transported, combustion derived dioxins and furans (HITES, 1990; KOESTER and HITES, 1992). Thus the anomalously high values suggest a local source. (There is a possibility that this peak concentration is associated with a small lumber mill immediately to the west of the sample location and there is, at present, a burning operation in the area (A. STRANG, Howe Sound Pulp and Paper, *personal communication*). Further chemical analyses are presently being undertaken from nearby sediment samples to confirm its presence.

The decline of values on both sides of the Port Mellon plant suggests that ebb and flood tidal currents are dispersing contaminants to the north and south. Unlike Upper Howe Sound where the influence of the Squamish River is unidirectional and serves to override the tidal influence, Thornbrough Channel is entirely tidally dominated. In an environment of total deposition, particles may be deposited at both slack high and low water periods giving rise to decreasing contamination on either side of their source. A further explanation for these findings may be the result of a dumpsite adjacent to the plant. The low R^2 values in Thornbrough Channel attest to the effects of dumped material disturbing the natural transport


(a) UPPER HOWE SOUND
total dioxins
total furans
N S
(thousands)
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-4·7
-2·6
0·9
1·2
2·2
4·2
6·1
8·1
10·3
Distance from Woodfibre (km)
(b) RAMILLIES AND MONTAGU CHANNELS
RAMILLIES
N S
total dioxins
total furans
MONTAGU
N S
(thousands)
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
0·0
2·5
5·3
7·0
11·1
13·8
0·0
2·9
5·7
8·6
Distance down channel (km)



←

Figure 10. Total dioxin and furan flux (pg g^{-1} × mm a^{-1}) with distance down each channel.

regime. The movement of dumped material would be dependant on tidal conditions at the time of dumping and would, therefore, allow an equal probability of dispersal in either direction.

The higher contaminant concentrations to the south of Port Mellon may be simply the result of incorrectly applying a constant deposition rate for the whole of Thornbrough Channel. Another possibility is that the south-directed ebb is both weaker and of less duration than the north-directed flood. This would result in a smaller dispersion of contaminants to the south and, hence, higher concentrations. The strongest argument in favour of northward transport predominating is found in the contaminant levels of Ramillies and Montagu Channels where concentrations are significantly higher in the former (Table 2; Figure 10b). There is no other reason for Ramillies Channel to have higher levels of contamination than Montagu Channel other than they are being supplied by the transport regime out of Thornbrough Channel as determined by the transport pathways.

Unfortunately, there are no contaminant data available for the remaining transport environments (Table 1). Further analyses are planned for the future; however, on the basis of the transport pathways, it is unlikely that there are contaminants of any significance in the Southern Gambier Island regime where there is no source. It might be expected to find contaminants associated with the Fraser River in the sediments of the Queen Charlotte Channel and Strait of Georgia regimes. If present at all, concentrations should decrease along the directions of transport. The lowest values anywhere should be found in Collingwood Channel and Barfleur Passage where the sediments are undergoing slight net erosion.

SUMMARY AND CONCLUSIONS

(1) A sediment trend analysis was performed on about 820 grain-size distributions taken from

the bottom sediments of Howe Sound and the adjacent Strait of Georgia. The technique enabled patterns of net sediment transport to be determined, as well as the depositional behaviour of the sediments.

(2) The trends indicate that the transport regime from Squamish to Bowyer Island is driven largely by the inflowing Squamish River. From Squamish to the sill, the derived X-distributions are typical of total deposition. Thus, sediments tend to fine in the down-fjord direction and, once deposited, undergo no further transport. South of the sill, however, the X-distributions are horizontal, a form that suggests that for the fine sediment remaining in transport, there is an equal probability of all sizes being deposited (*i.e.*, a size-sorting is no longer taking place).

(3) Sediments in Thornbrough Channel show transport in the north direction indicating a clockwise regime around Gambier Island. As in Upper Howe Sound, the X-distribution is one of total deposition. Low R^2 values for this region are explained by a dumpsite in the middle of the Channel adjacent to Port Mellon and the influence of numerous creeks debouching into the fjord. Total deposition of sediments is also observed in the bays along the south side of Gambier Island.

(4) Queen Charlotte Channel is dominated by northward transport of material originating from the Strait of Georgia and undergoing total deposition. The effects of this transport regime extend to the vicinity of Bowyer Island where the sediments meet the southward trending Ramillies and Montagu Channel regimes. These sediments are probably derived from the Fraser River, the North Arm tributary of which is only 10 km away.

(5) On the west side of Bowen Island through Collingwood Channel and Barfleur Passage, there is also a northward transport regime with X-distributions indicative of slight net erosion.

(6) Contaminant data (dioxins and furans) from the sediments of Upper Howe Sound, Ramillies and Montagu Channels, and Thornbrough Channel support the interpretation of the transport pathways derived by the sediment trend analysis. In the environments of total deposition (Upper Howe Sound and Thornbrough Channel), contaminant peaks are related to the location of the pulp mills. Where the X-distributions are horizontal (Ramillies and Montagu Channels), contaminant levels show relatively little variation. Significantly higher contaminant levels are found in Ramillies Channel compared to Montagu Channel reflecting an input from Thornbrough Channel.

(7) Although there are no contaminant data from the remaining transport environments, levels are not expected to be high for Southern Gambier Island where there is no source. There may be contaminants associated with the Fraser River in Queen Charlotte Sound and in the Strait of Georgia, and these would be expected to decrease along the directions of transport. In Collingwood Channel and Barfleur Passage where there is slight net erosion, no accumulation of contaminated sediments can be anticipated.

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