Piper, D.J.W. and Fehr, S.D., 1991, Radiocarbon chronology of the late Quaternary sections on the inner and middle Scotian Shelf, south of Nova Scotia: Geological Survey of Canada, Paper 91-1E, p. 321-325.

Piper, D.J.W., Mudie, P.J., Letson, J.R.R., Barnes, N.E. and Iuliucci, R.J., 1986, The marine geology of the inner Scotian Shelf off the South Shore, Nova Scotia: Geological Survey of Canada, Paper 85-19, 65 p.

Piper, D.J.W. and Normark, W.R., 1989, Later Cenozoic sea-level changes and the onset of glaciation: impact on continental slope progradation off eastern Canada: Marine and Petroleum Geology, v. 6, p. 336-348.

Shaw, J., 1985, Aqueous deposits in the glacial environment, *in* Ashley, G.M., Shaw, J. and Smith, N.D., eds., Glacial sedimentary environments: Society of Economic Paleontologists and Mineralogists, Short Course 16, p. 53-61.

Shaw, J. and Forbes, D.L., 1990, Late Quaternary sedimentation in St. George's Bay, southwest Newfoundland: acoustic stratigraphy and seabed deposits: Canadian Journal of Earth Science, v. 27, p. 964-983.

Shepard, F.P., 1931, St. Lawrence (Cabot Strait) submarine trough: Geological Society of America, Bulletin, v. 42, p. 853-864.

Smith, W.H.F. and Wessel, P., 1990, Gridding with continuous splines in tension: Geophysics, v. 55, p. 293-305.

Taylor, E.G.R., 1971, The Haven-finding art: A history of navigation from Odysseus to Captain Cook: Elsevier, New York, 310 p.

Varma, H.P., Boudreau, H. and Prime W., 1990, A Data Structure for Spatio-Temporal database: International Hydrographic Review, Monaco, v. 67(1), p. 71-92.

Vilks, G., Buckley, D.E. and Keigwin, L., 1985, Late Quaternary sedimentation on the Southeast Sohm Abyssal Plain: Sedimentology, v. 32, p. 69-82.

Wade, J.A. and MacLean, B.C., 1990, Aspects of the geology of the Scotian Basin from recent seismic and well data, *in* Keen, M.J. and Williams, G.L., eds., Geology of the Continental Margin of Eastern Canada: Geological Survey of Canada, Geology of Canada, v. 2, (also Geological Society of America, The Geology of North America, v. I-1), p. 190-238.

Wang, Y., Piper, D.J.W. and Vilks, G., 1982, Surface textures of turbidite sand grains, Laurentian Fan and Sohm Abyssal Plain: Sedimentology, v. 29, p. 727-736.

Wingfield, R., 1990, The origin of major incisions within the Pleistocene deposits of the North Sea: Marine Geology, v. 91, p. 31-52.

Wilkes, C., 1848, On the Depth and Saltness of the Ocean: American Journal of Science and Art, v. 5(13), p. 41-48. [quoted in S. Shlee, 1973, The Edge of an Unfamiliar World: E.P. Dutton and Co., New York, 398 p.]

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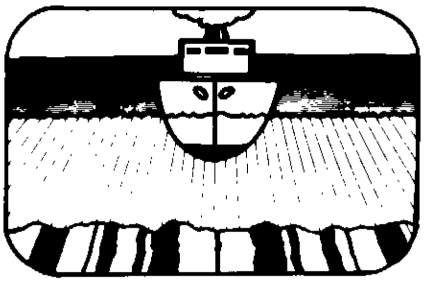

The Seasonal Distribution of Suspended Particles and Their Iron and Manganese Loading in a Glacial Runoff Fiord

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SUMMARY

Three mechanisms are responsible for the distribution of inorganic suspended particulate matter in a glacially influenced fiord such as Knight Inlet, British Columbia. The most important is the influx of sediment from rivers draining hinterland ice fields, with maximum input levels reached in the summer melt season and during the autumn period of flash floods. Sediment can also enter a fiord from the sea: 1) within the return flow of estuarine circulation that is fully developed during the late spring through early autumn, and 2) as part of deep shelf water that exchanges and flushes out the deep water of the fiord basin, particularly during the winter season. The third mechanism for sediment accumulating on the sea floor is through the action of episodic turbidity currents. These sediment gravity flows carry coarse delta-front sediments to the otherwise muddy basin floor. The relative abundance of particulate iron within the suspended sediment load directly relates to higher levels of iron in glacially derived particles issuing from river mouths at the head of the fiord. Elevated levels of particulate manganese may be a result of turbidity currents. They are observed in the water column nearest the sea floor where circulation and geochemical conditions would normally preclude their existence.

INTRODUCTION

A fiord is a deep high-latitude estuary which has been (or is presently being) excavated or modified by land-based ice (Syvitski *et al.*, 1987). Since fiords are at least partially ice scoured, the typical configuration is a long narrow deep and steep-sided inlet, which is frequently branched and sinuous, but may be remarkably straight in whole or in part where the ice has followed major fault zones. Fiords usually, but not inevitably, contain one or more submarine sills: bathymetric highs that separate the deep water of basins. The internal basins defined by these sills are characteristic features of fiords, which determine many of their distinctive physical and biogeochemical characteristics. Except for some polar inlets during the winter, all fiords are estuaries. Major freshwater inflow is likely to be at the head, and the brackish water typically flows toward the mouth as a surface plume. As with all estuaries, fiords are therefore transition regions between the land and the open ocean, regions of strong physical and chemical gradients where fresh and salt waters mix and react.

Fiords encompass a number of distinctive oceanographic environments, which make them particularly exciting for estuarine research. The near-surface "estuarine zone", basically common to all estuaries, is underlain by marine water which, in silled fiords, may be physically restrained in basin enclosures. Such coastal-zone, mini-ocean basins offer unique opportunities for studying terrestrial input into quasi-closed marine systems. Often the circulation above and below the top of the sill is poorly coupled, and, in deep fiords, processes and reactions within the basins may be spatially and temporally separated from those occurring in the upper-zone estuarine environment.

Fiords receive water from land *via* rivers that drain the hinterland mountains and ice fields, and as deep water circulation from the open ocean. These water pathways carry sediment in suspension, most of which settles to the sea floor creating a sedimentary cover characteristic of fiord environments. The character and distribution of suspended particles within fiords receiving glacier meltwater is influenced strongly by the seasonality of fluvial discharge, the largest source of sediment, and the production of biological detritus. From the work of Syvitski and Murray (1981), we know that the turbid plume issuing from a river mouth carries sediment down the length of the fiord quickly, while this fresh water slowly mixes with sea water.

Flocculation is the process that holds particles together in spite of repulsive electrostatic forces that are part of the natural chemical makeup of soil particles. Ions within a saline solution neutralize the repulsive forces, allowing Van der Waals binding to occur. Once particles have joined, the resultant settling velocity of the flocs is usually greater than that of the individual components. Although flocculation occurs within the brackish waters of a fiord plume, mixing is the dominant means for sediment to exit the plume and enter the marine water. This is particularly true for the fine silt and clay-sized particles. Particles may settle through the water column of a fiord on the order of days, even though the water depth may be hundreds of metres: an observation which highlights processes that enhance the settling velocity of a suspended particle. Syvitski and Murray (1981) further demonstrated the causal link between river discharge, the size of particulates within the suspended load, and the observed sedimentation rate within a fiord.

Syvitski *et al.* (1985) later showed how a fiord environment can be divided into a proximal zone near the river mouth and a distal zone, as a function of the hydrodynamic behaviour of the buoyant (lower density or hypopycnal) plume issuing from a river mouth. As a result of flocculation in the proximal zone, where particles are clumped together, all particles smaller than 10 μm attain similar settling velocities beneath the river plume: around 100 metres per day. This settling rate is some 10-1000 times larger than if flocculation did not occur and individual particles settled as predicted by Stoke's Settling Theory (*cf.* Syvitski, 1991). For sand-sized particles greater than 100 μm in diameter, Reynold's Drag Law holds (*cf.* Syvitski, 1991). In the more distal zone, the vertical flux of particles is controlled more by biogeochemical interactions such as planktonic pelletization of fine particles, flocculation (which occurs within rather than below the surface plume in contrast to the proximal zone), and agglomerative processes including the role of bacteria. The suspended load within a river plume decreases as a power-law function of distance from the river mouth.

Metal concentrations in coastal marine systems are also strongly affected by river discharge and water circulation events acting upon both the particulate and dissolved metal fractions (Sugai, 1987). The transport pathways of the metals depend on the nature of the input as well as the effects of geochemical and biological processes acting upon the introduced metals. The source of these metals can be terrestrial environments, through riverine or aerosol input, adjacent marine waters, or the benthic sediments. fiords receiving a preponderance of glacial runoff, with their high levels of finely divided particulates (Syvitski, in press), thus offer an opportunity to examine the spatial (distance from source) and seasonal effects of suspended particulate matter and their metal loadings.

Our objective is to discuss an unpublished data set on the spatial and temporal distribution of suspended particulate matter in Knight Inlet, British Columbia, particularly in light of a recent theory on particle scavenging within a buoyant and turbid river plume (Syvitski *et al.*, 1988). This fiord suspended sediment data set is one of the few in terms of the completeness of the seasonal coverage. The data were obtained during ten cruises from October 1974 through September 1975. The work was initiated to examine the factors that affect the biological availability of copper in a deep coastal basin receiving high levels of inorganic particles (Lewis, 1976). The oceanographic and biological data formed part of a Ph.D. thesis (Stone, 1977). Herein, we offer an oceanographic description of the fiord and the suspended sediment distribution through the changing seasonal cycles, including the iron and manganese loadings on the suspended particles.

Environmental Setting

Knight Inlet is located 350 km northwest of Vancouver, on the mainland coast of British Columbia. It is long and narrow, and penetrates some 110 km into the Coast Range Mountains that contain large ice fields. The connection with the Pacific Ocean is through Queen Charlotte Strait, between the northern end of Vancouver Island and the mainland of British Columbia (Fig. 1). Two shallow sills, approximately 65 m deep, partition the fiord into a 540 m deep inner basin and a 200 m deep outer basin.

The hydrologic cycle of the fiord has a pronounced seasonal variation with high summer and low winter discharge. Summer discharge is initially affected by snow melt, which peaks in June (>1000 $m^3 \cdot s^{-1}$), followed by glacier melt, which peaks in July/August. The glacial meltwater contains the highest concentrations of suspended mineral grains (>500 $g \cdot m^{-3}$). Winter discharge (<100 $m^3 \cdot s^{-1}$) is primarily a result of lowland drainage and carries very little sediment (<5 $g \cdot m^{-3}$). The major fluvial inputs are the Klinaklini and Franklin rivers. Both enter at the head of the fiord and account for 95% of the glacially derived material that reaches the basin (Syvitski *et al.*, 1988). Small rivers and streams also enter along the sides of the fiord, but most have a very local influence.

Near the mouths of the two major rivers, expansive sand and gravel deltas have formed: turbid river plumes carrying silt and clay extend well down the fiord during periods of peak summer discharge. The coarser silt particles are deposited on the sea floor proximal to the river mouths as a unique sedimentary unit: the prodelta facies (Fig. 2). The exception is a spatially complex channel system, cut into the prodelta muds and floored with turbidite sands (Syvitski *et al.*, 1988), which forms another unique sedimentary unit, namely, the gravity flow and overspill transition facies (Fig. 2) (*cf.* Schafer *et al.*, 1989). The channels are the result of episodic sediment gravity flows, originating near the fiord-head deltas as a consequence

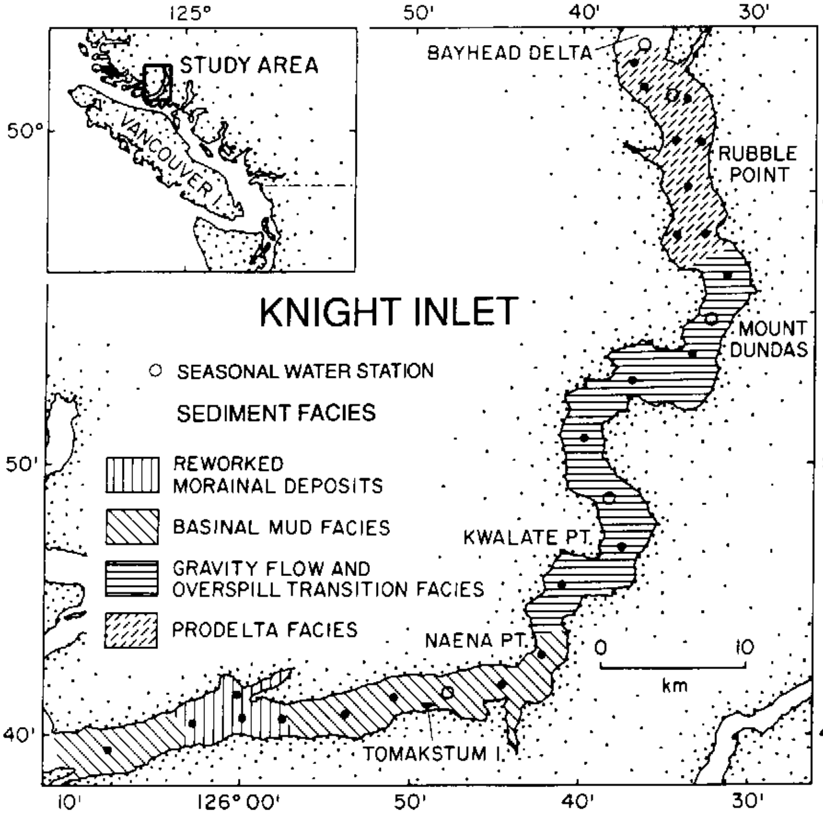

Figure 1 *Location of Knight Inlet, British Columbia, showing appropriate sediment and water stations. Sediment samples are located with the black dots. The Kliniklini and Franklin rivers flow into the head of the fiord (shown as bayhead deltas). Sediment lithofacies are after Schafer* et al. *(1989): morainal deposits are mostly gravels and sands; basinal muds are composed largely of very fine silts and clay, gravity flow facies are interlayered sands and muds; and prodelta facies are largely medium to coarse silts.*

of very high rates of sedimentation (Syvitski and Farrow, 1983). These gravity flows would be expected to reintroduce particulates and dissolved metals, contained in interstitial water, back into the water column. In the most distal reaches of the fiord basin, where gravity flow sands do not extend, the finest fraction of river plume sediment is deposited as a basinal mud or clay facies (Fig. 2). The basin is enclosed by a sill composed of coarse-grained sediment deposited in front of a glacier that occupied the fiord during the last ice age. Due to high tidal currents that flow over this sill, these morainal deposits are reworked into a lag of boulders and gravel (Fig. 2).

METHODS

Details of methodologies, cruise dates and parameters measured for the various stations and depths are in Lewis (1976). Water was measured (Fig. 1) for temperature, salinity and oxygen (*cf.* data reports 37 and 41 from the Institute of Oceanography, University of British Columbia), suspended load and their total particulate metals (Fe and Mn used in this paper), nutrients, and chlorophyll "a". Water samples (3.5 L) were filtered through pre-weighed and pre-cleaned 0.45 µm nominal pore size filters, in a nitrogen environment (20 psi). Metal concentrations were determined, using flame atomic absorption spectrophotometry (Techtron AA4), from the suspended sediment retained on the filters, after digestion in heated 4:1 nitric: perchloric acid, evaporated to dryness, and resuspended in 0.1 N HCl. Precision, expressed as relative standard deviation, was 7.5% for manganese (at 0.81 $\mu g \cdot mg^{-1}$ sediment), and 3.3% for iron (at 35.29 $\mu g \cdot mg^{-1}$ sediment). Major oxide components of the suspended sediment determined by X-ray fluorescence are also available in Lewis (1976).

Sea-floor samples (Fig. 1) were collected using a Shipek grab sampler. Size distribution methods and data are described in Schafer *et al.* (1989). Metal analysis of these benthic samples is as described for suspended sediments. Particle size of the suspended particulate matter (SPM) for river and fiord samples was determined using a Coulter Counter and a 100 µm aperture tube.

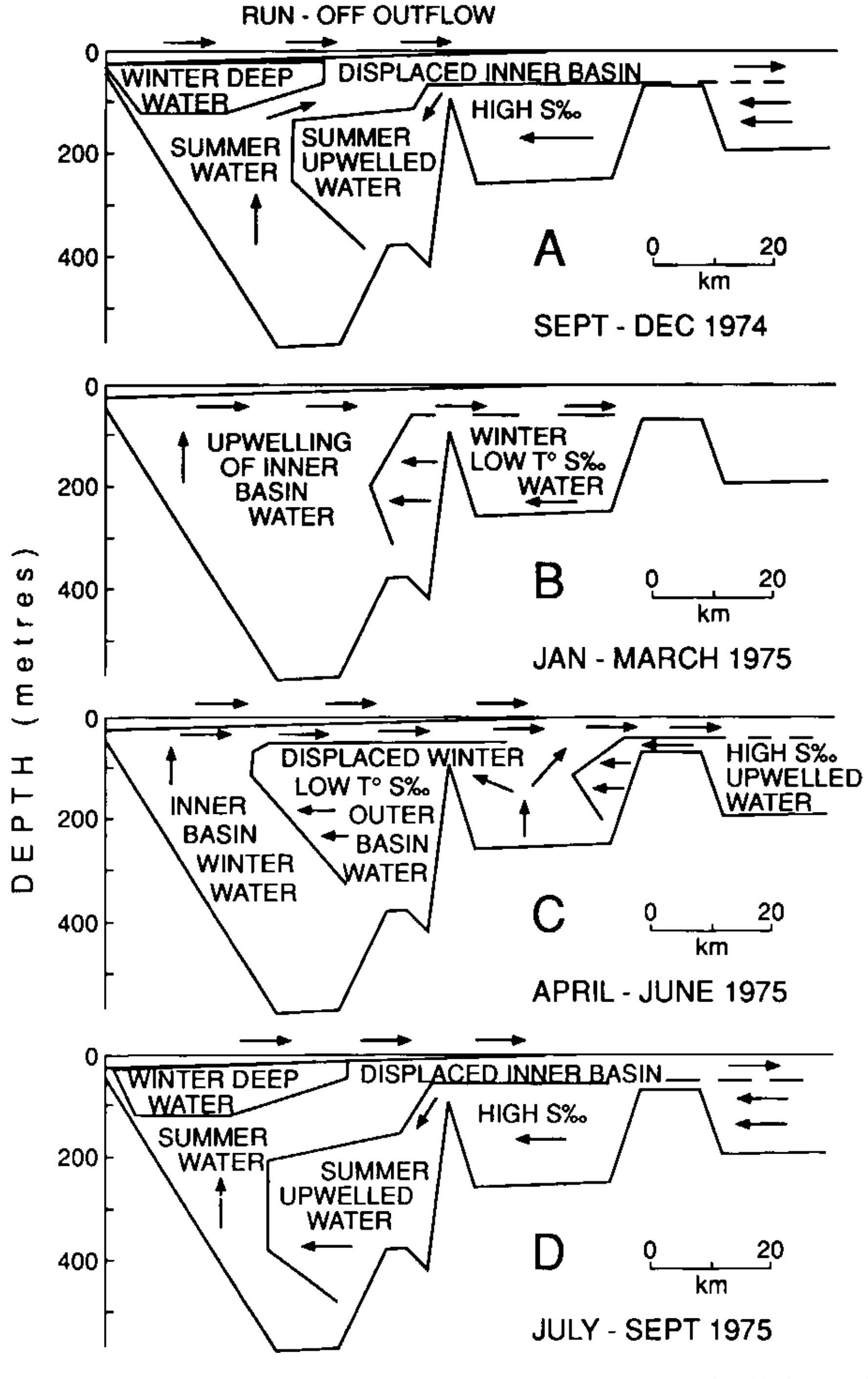

Figure 2 *Generalized schematic of the principal water masses in Knight Inlet, and their residual transport during each of the four seasons. The open ocean is to the right. The symbol for salinity is given as S ‰.*

KNIGHT INLET OCEANOGRAPHY

The normal near-surface circulation is a shallow outflow of freshwater runoff down the fiord, producing a strong density gradient between the surface fresh water and denser sea water (*i.e.*, a pycnocline), generally in the upper 10 m (Fig. 2) (*cf.* Pickard, 1961). Since the majority of the runoff is from two glacially fed rivers, the Klinaklini and Franklin rivers, the discharge of fresh water into the fiord is characterized by a winter minimum and an intense summer maximum. The salinity of the surface outflow increases in a seaward direction as a result of entrainment. This produces the subsurface inflow of saline water characteristic of estuarine circulation. The salinity of the inflowing subsurface water reaches a maximum in late summer and early autumn, as upwelled open coast water is transported from Queen Charlotte Strait (Dodimead and Pickard, 1967). Although the inner sill restricts exchange between the two basins, the entrance of the high salinity water into the inner basin is enough to cause density-driven replacement of part or all of the deep water (Fig. 2).

During the 1974-75 study period, the high salinity subsurface inflow (deep water renewal) was evident until December 1974. Surface outflow of freshwater runoff decreased during the autumn period (Fig. 2). Minimal freshwater runoff occurred during the period January-March 1975. A cold low-salinity water mass occupied the entire outer basin, formed *in situ* by a combination of surface cooling, mixing and diffusion (for a detailed discussion see Farmer and Freeland, 1983). Some of this water moved into the inner basin during the January-March period, replacing warmer water which moved seaward as a subsurface flow. Between April and June

1975, increased river inflow was apparent as a surface current that flowed down the fiord toward the ocean (Fig. 2). An even more pronounced and glacially derived outflow was evident between July and September. The salinity of Queen Charlotte Strait increased during this period as a result of offshore upwelling (Stone, 1977). This created a density gradient between Queen Charlotte Strait and the outer basin of Knight Inlet, providing higher salinity water in the subsurface water that flowed up the fiord into the inner basin. Displaced inner basin water moved toward the upper end of the fiord and then seaward.

Theoretical studies such as that of Winter (1973) and direct observations (*e.g.*, Pickard and Rodgers, 1959; Farmer and Freeland, 1983) show that the current velocity within a fiord often decreases with depth, and that flow can be in opposing directions depending on the depth. This is important in the present study because of the effect of water flow on the transport of particulate materials.

SUSPENDED PARTICULATE MATTER

The distribution of suspended particulate matter (SPM) within the waters of Knight Inlet is typical of other British Columbia inlets fed by glacier-melt rivers (*e.g.*, Howe Sound: Syvitski and Murray, 1981; Bute Inlet: Syvitski *et al.*, 1985). The most turbid water is associated with the river plume outflow that is confined to the estuarine circulation cell within the upper-water column, and that is well developed during the spring and summer (Fig. 3). The particle scavenging model developed in Syvitski *et al.* (1988) can be appropriately applied to our data set and inferences made on the seasonal SPM settling characteristics and sedimentation rates within Knight Inlet.

At any given time, SPM enters the fiord from a river with an initial concentration, C_o, and subsequently undergoes both settling and advection down the fiord. The inventory at the river mouth, I_o in units of mass per cross-sectional area ($M \cdot L^{-2}$), is the initial concentration integrated over the channel depth H_o. If we assume uniform size particles that have a first-order removal from the water column as a function of time, t, then:

$$dI/dt = -\lambda I \qquad (1)$$

which can be integrated under the boundary condition $I = I_o$ at $t = 0$, to give,

$$I = I_o e^{-\lambda t} \qquad (2)$$

where λ is a first-order removal rate-constant, in units of T^{-1}. For the case of a piston or plug flow, $t = x/u_o$, where u_o is the longitudinal plume velocity, x is distance along the plume and equation (2) becomes:

$$I = I_o e^{-\lambda x/u_o} \qquad (3)$$

The removal constant of each size class depends on a particle's *in situ* scavenging rate, *i.e.*, as affected by flocculation, agglomeration and zooplankton pelletization. To estimate λ, only the inorganic (mineral grain) constituent can be considered. The biogenic component is background noise,

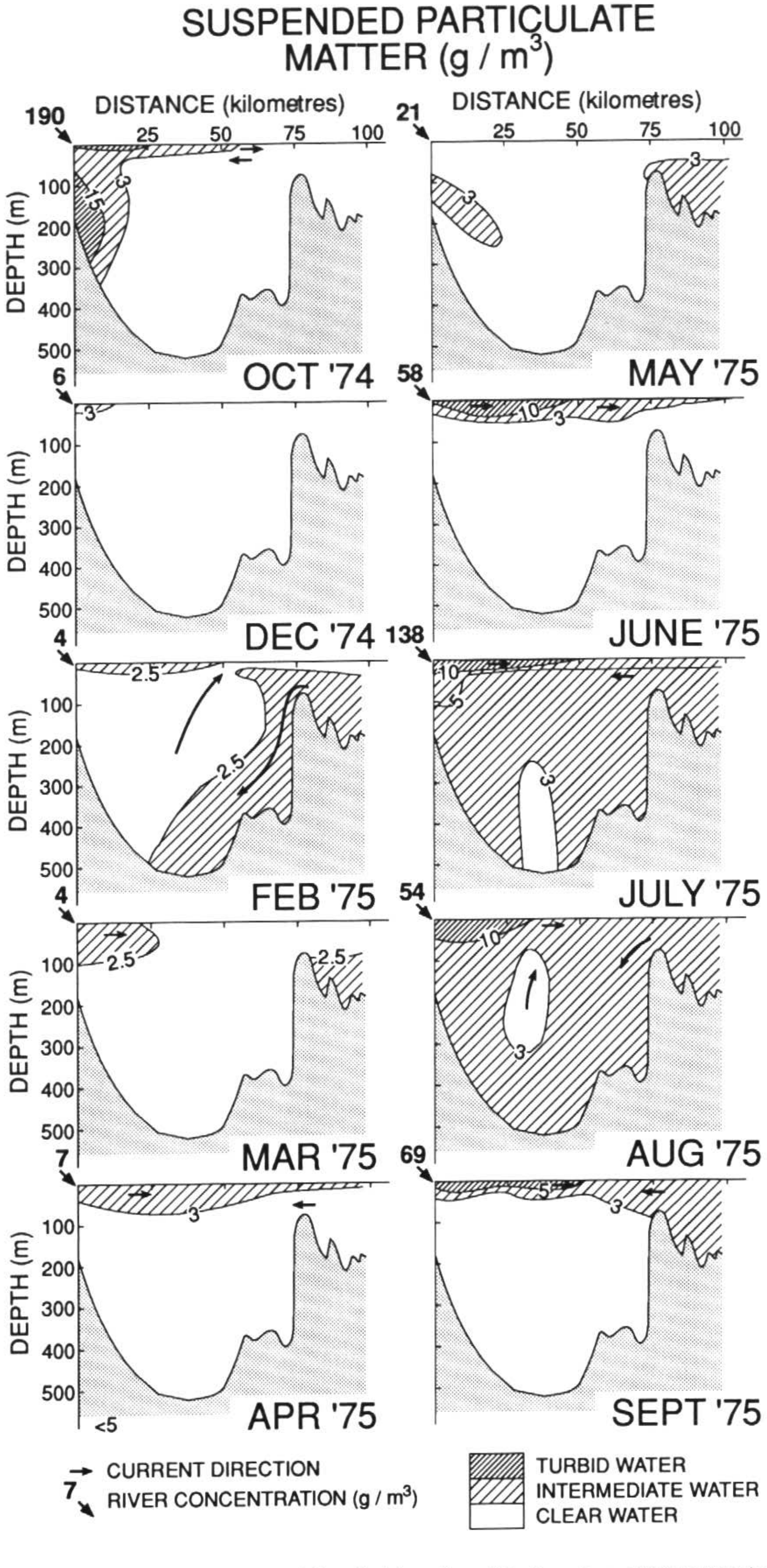

Figure 3 *The distribution of suspended particulate matter within the waters of Knight Inlet during 1974/75. The contoured intervals (mg•L⁻¹ or g•m⁻³) are variable and were chosen to best reflect the sediment distribution pattern through the various seasons.*

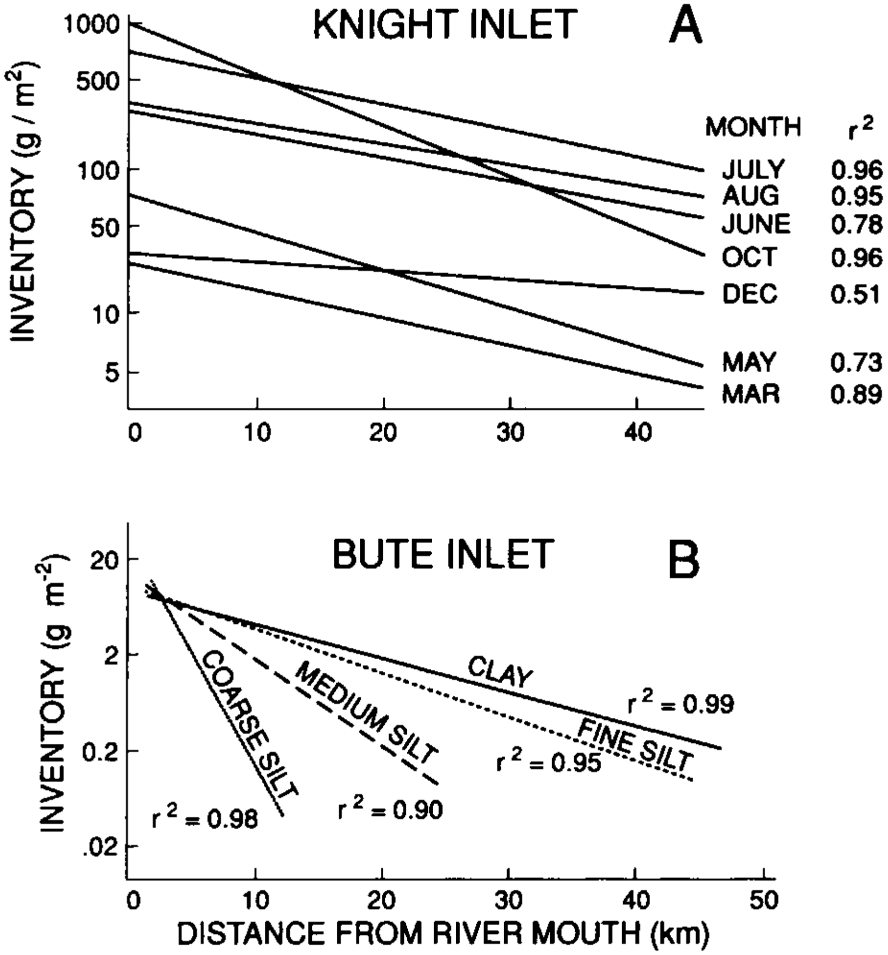

Figure 4 (**A**) *Seasonal inventory regressions of suspended load within the river plume of Knight Inlet: r^2 is the variance accounted, r is the correlation coefficient.* (**B**) *Particle inventory within the river plume of neighbouring Bute Inlet during summer discharge; the inventory is subdivided into four size fractions (after Syvitski* et al., *1988).*

and within our data, we use a 2 $g \cdot m^{-3}$ filter (based on typical background concentration levels, *cf.* Fig. 3). The inventory of SPM within each vertical slice of the surface plume (to a depth of 40 m) is calculated from the integration of samples that were collected depths of at 0, 5, 10 and 30 m. Semi-log regression analysis of the river plume SPM data is illustrated in Figure 4A. The x-axis is distance from the fiord head and the y-axis is the SPM inventory plotted as natural logrithms. The y-ordinate provides I_o. The slope of each regression line provides λ / u_o. With knowledge of u_o, λ may be calculated. Table 1 provides the salient information.

Syvitski *et al.* (1988) found that a separate removal rate constant exists for each particle size. They found that λ was 12.3 day^{-1} for coarse silt, 4.7 day^{-1} for medium silt, 2.7 day^{-1} for fine silt, and 2.0 day^{-1} for clay-sized particles (Fig. 4B). Thus, we may infer a preponderance of a certain grain size within our seasonal SPM data based on the determined value of the removal rate constant. We note that for the winter months, the SPM is composed predominantly of clay-sized particulates. In the spring, a time of river runoff from snow melt, the SPM is mostly fine silts. In the summer, a period of glacier melt, the SPM comprises medium silt particles. During the autumn period of flash floods, the grain size is that of coarse silt.

If we assume that SPM removal from the system occurs solely by sedimentation at a rate Z(x), in units of mass per area per time, then:

$$Z(x) = \lambda I \tag{4}$$

and from equation (3)

$$Z(x) = \lambda I_o e^{-(\lambda / u_o) x}$$

Table 1 Input values to particle scavenging model from monthly observations in Knight Inlet, British Columbia. See text for a complete description of symbols. Note: no information was collected for November and January. February and April had seasonally low values of suspended load and a removal rate constant could be discerned. λ could not be estimated for September.

Month	Discharge[1] Q_o ($m^3 \cdot s^{-1}$)	Concentration[2] C_o ($g \cdot m^{-3}$)	River Velocity[3] u_o ($m \cdot s^{-1}$)	Removal Rate[4] λ (day^{-1})	Grain Size[5] d (μm)	Sedimentation Rate[6] Z_o ($g \cdot m^{-2} day^{-1}$)	Accumulation Rate[7] $\partial h / \partial t$ ($mm \cdot mo^{-1}$)
Oct	400	190	1.32	9.2	50	5300	31.0
Dec	120	6	0.44	0.5	0.5	8	0.1
Feb	100	4	0.31	–	–	–	–
Mar	90	4	0.22	0.8	0.5	13	0.1
Apr	110	7	0.35	–	–	–	–
May	200	21	0.44	2.3	5	220	1.8
Jun	450	58	0.87	2.6	5	780	9.2
Jul	600	138	1.31	4.6	30	2900	31.3
Aug	700	54	1.35	4.6	30	1300	14.0
Sep	600	69	1.19	–	–	–	–

Notes:

[1] discharge listed is 1977-1984 monthly average.

[2] concentration calculated from the average of four instantaneous measurements of the Kliniklini and Franklin rivers (Lewis, 1976).

[3] river velocities after Water Survey of Canada field notes on river flow (Syvitski *et al.*, 1988).

[4] removal rate is from surface plume inventory according to method outlined in text.

[5] grain size is inferred grain size of typically settling particle associated with scavenging rates (after Syvitski *et al.*, 1988).

[6] sedimentation rate is maximum rate predicted for the river mouth using equation (5) in text.

[7] accumulation rate of sediment on the sea floor *at 10 km from the river mouth* using equations pertaining to the spreading of a bouyant-free two-dimensional jet (*cf.* equation 11c in Syvitski *et al.*, 1988); also assumes a bulk sediment density of 1500 $kg \cdot m^{-3}$.

At $t = 0$, the maximum sedimentation flux, Z_o, may be expressed in terms of sediment delivery by any one of the following relationships:

$$Z_o = \lambda I_o \tag{5a}$$

[the removal constant times the initial river plume inventory] or after subsituting river mouth depth times the suspended concentration for plume inventory

$$Z_o = \lambda H_o C_o$$

or after substituting the ratio of suspended load Q_s, to river mouth discharge Q_o, for suspended concentration

$$Z_o = \lambda H_o Q_s Q_o^{-1}$$

or after substituting the components of river discharge: river mouth depth, width b_o, and velocity

$$Z_o = \lambda H_o Q_s (u_o b_o H_o)^{-1}$$

and thus

$$Z_o = \lambda Q_s (u_o b_o)^{-1} \tag{5b}$$

In Table 1, we provide Z_o values for the various seasons. As expected, the summer months, dominated by glacier melt, and the fall period, affected by flash floods, are associated with the largest river mouth sedimentation rates.

Plume velocity does not behave as a simple plug flow, but is variable with distance from the river mouth depending on inertial, frictional and buoyant forces. If we assume that the velocity distribution within the Knight Inlet river plume can be described as a buoyancy-dominated, free two-dimensional jet, which models marine basins that are highly stratified (*cf.* Syvitski *et al.*, 1988), then along the axis of the plume,

for $x \leq 5.2b_o$ (6)

$$Z(x) = Z_o e^{-(\lambda/u_o)x}$$

for $5.2b_o < x \leq x_b$

$$Z(x,y) = Z_o \exp[-\lambda(1.76\, b_o/u_o + 0.29\, x^{1.5}/u_o\, b_o^{0.5})]$$

for $x > x_b$

$$Z(x,y) = Z_o \exp[-\lambda(1.76\, b_o/u_o + 0.15 x^{1.5}/u_o\, b_o^{0.5})]$$

where x_b is the distance after which plume spreading is affected by fiord walls. The three parts of equation (6) refer to three dynamic zones of the river plume. Nearest the river mouth is a zone of flow establishment where the center of the plume continues to behave as a plug flow out to a distance of $5.2b_o$. Next is a zone of established flow where the axis velocity decreases as the plume spreads. In the far zone, plume spreading is affected and constrained by the basin walls from a distance x_b, beyond which the residual plume velocity remains more or less constant.

In Table 1, we use equation (6) to predict the accumulation of hemipelagic sediment on the sea floor, in units of millimetres per month, at a distance of 10 km from the river mouth. (Values predicted for sites closer or farther away from the river mouth would be larger or smaller, respectively, but would show the same magnitude of seasonal change.) If we interpolate between these

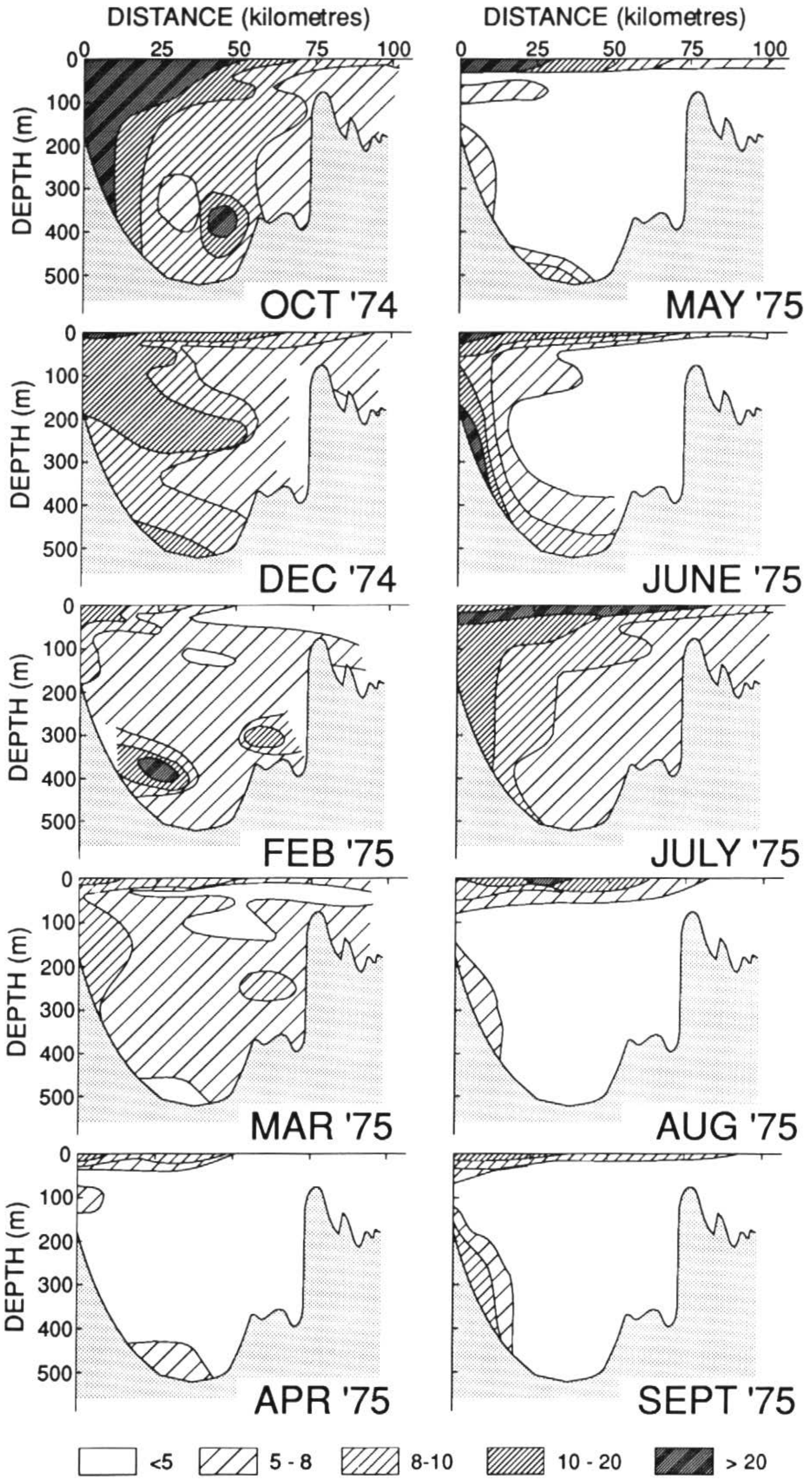

Figure 5 *The distribution of particulate iron (PFe in µg•mg⁻¹ of SPM) within the waters of Knight Inlet during 1974/75.*

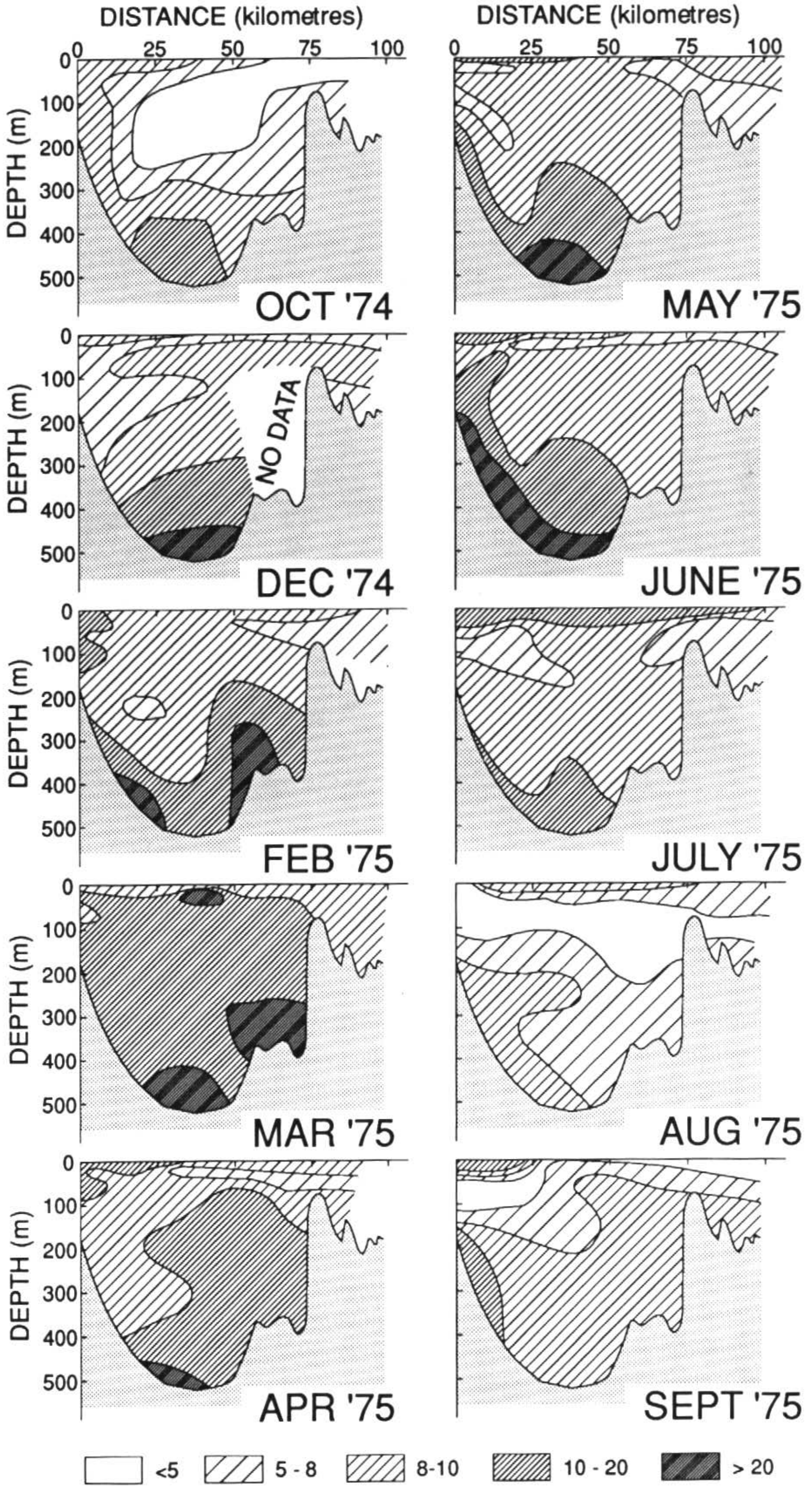

Figure 6 *The distribution of particulate manganese (PMn in µg•mg⁻¹ of SPM) within the waters of Knight Inlet during 1974/75.*

values for the months where we have missing data, then this position has an annual accumulation rate of just under one centimetre per year. One-third of this sediment accumulates during July, another third during the rest of the spring and summer, and one-third during the autumn flash floods. Almost no sediment accumulates for five months of the year, during late autumn through early spring.

The deep water inflows into the inner basin of Knight Inlet occur during the fall and are associated with clean outer basin water. As winter progresses, more turbid shelf water is involved in the flushing out of inner basin water (Fig. 3: February). Bottom water near the fiord-head deltas can also be very turbid (Fig. 3: October). Such high SPM values may relate to turbidity current events. Recent monitoring experiments in neighboring Bute Inlet have recorded many episodic turbidity currents with flow thicknesses of more than 30 m, some travelling distances of more than 50 km (Prior *et al.*, 1987).

METALS

Metals enter the inner basin from the ocean and from hinterland run-off, in both dissolved and particulate form. Unknown amounts also enter as aerosols, through slides, and in biological debris (primarily logs), but these are presumed to be of small magnitude and unimportant in the overall flux of metals. Seasonal changes in run-off will affect the concentration of particulate metals in the water column. Heavy run-off carrying sediment of glacial origin introduces large amounts of finely divided particles which contain metals, but which also can affect the concentration of dissolved metals through sorption and sedimentation processes (Syvitski *et al.*, 1987). Uptake of dissolved metals by phytoplankton will cause an increase in particulate metal with an accompanying decrease in dissolved metal. In this latter case, the change in metal concentration will be dependent upon the level of biological activity, the nature of the organism, and the biological availability of the metal (Lewis and Syvitski, 1983).

Glacial outflow not only introduces metal-containing particles into the inner basin, but also transports them seaward. Although the sill separating the inner and outer basins prevents complete exchange of water between the basins, the subsurface inflow above the sill depth will transport some of the biogenic material produced in the outer basin into the inner basin. This return current will also reintroduce some of the particles that settle out of the downfiord surface flow. Since the rate of subsurface inflow is related to the rate of surface outflow, upfiord transport will increase during glacial outflow when there is increased near-surface downfiord transport of glacial particles.

The particulate metal load in the water column (in units of µg of metal per L of water) of Knight Inlet was measured monthly and found to be positively associated ($P << 0.01$) with the suspended sediment (SPM) concentration. However, when considering the relative abundance of a metal within the suspended sediments (in units of µg of metal per mg of suspended sediment), the only significant and positive correlation (r^2 = 0.94) is between SPM and iron. Iron is, in fact, a major constituent of the silicate and oxide minerals that dominate the glacial flour constituents entering British Columbia fiords (Syvitski *et al.*, 1985; Schafer *et al.*, 1989). For instance, Syvitski and Farrow (1983) noted that substantial portions of the channel sands of the Klinaklini delta were cemented by iron oxyhydroxides. Particulate iron concentrations (mean of 33 µg Fe•mg^{-1} of SPM) at the head of the fiord and in the rivers were: 1) consistently higher than surface water collected in the more distal portions of the plume (16 µg•mg^{-1}); 2) greatly higher than marine water collected below the plume (6 µg•mg^{-1}); and 3) similar to sea-floor samples (33 + 10 µg•mg^{-1}). Elevated particulate iron concentrations can occur along the entire inner basin as part of the shallow water river plume, especially during the peak periods of glacial run-off (Fig. 5). We observe no relationship (r^2 = 0.008 with n = 43) between the sea-floor particulate iron (P_bFe), also measured monthly, and the suspended particulate iron (P^sFe). Therefore, we suggest that the coarser grained SPM is largely responsible for the sediment that is sampled on the sea floor and that the finer grained SPM, with lower iron levels, is present only as a background through which the coarser grains settle.

Although the particulate manganese load (µg•L^{-1}) appears dependent on the suspended mineral load, the relative abundance of manganese (µg•mg^{-1} of SPM) is generally higher in the deep water (mean of 1.0 µg Mn•mg^{-1} of SPM) when compared to the river plume water (0.5 µg•mg^{-1}). In fact, the deeper water particulate Mn levels (P_sMn) are most similar to the river mouth values (0.9 µg•mg^{-1}), and are higher than even the sea-floor (P_bMn) levels (0.7 µg•mg^{-1}) in difference to iron (Fig. 6). We know that the bottom water in Knight Inlet is relatively stable, with annual temperature and salinity variations of ±0.5°C and 0.1‰, respectively (Farrow *et al.*, 1983). Levels of dissolved oxygen in the bottom water, although more variable (±0.8 mg•L^{-1}), remain high (>3 mg•L^{-1}). Thus, the increased content of particulate manganese would not be a result of dissolved manganese seasonally diffusing out from the sea floor, as proposed recently for two Alaskan fiords (Sugai, 1987). We suggest that the higher levels of particulate manganese within the deep water are a result of finer grained material remaining in suspension after the advent of turbidity currents. In such a scenario, labile manganese would be initially released from the pore waters during erosion of the sea floor (*i.e.*, Buckley and Winters, 1983), in our case by a turbidity current. This sudden release of labile manganese could become quickly re-adsorbed onto suspended particles within the oxygenated regime of the Knight Inlet bottom waters. The initiation of slide-generated turbidity currents can be the result of a myriad of triggering mechanisms (seismic activity, buoyancy draw-down during extremely low tides, wave action including the impact of internal waves, and oversteepening of proximal slopes). Therefore, the advent of a turbidity current may not necessarily be seasonal and synchronous with peak periods of discharge and sedimentation (Syvitski *et al.*, 1987).

Farrow *et al.* (1983) have previously noted the importance of turbidity currents for emplacing shallow water sediment into the deep basins of Knight Inlet, based on lithologic analysis of sediment cores. Syvitski *et al.* (1988) continued that study using unstable isotopes and demonstrated that the annual flux of turbidity current-transported sediment into the Knight Inlet inner basin may conservatively reach 10^6 tonnes per year.

In conclusion, our geologic and oceanographic data show that well-oxygenated fiords, such as Knight Inlet, are affected by the seasonality of river discharge and more episodically by turbidity currents. Both processes affect the rate of sediment accumulation on the sea floor and the distribution and metals and suspended sediment within the water column. The affect of turbidity currents on metal distribution is a new hypothesis and should be tested in other fiord environments. Our study indicates that the monitoring of toxic metal transport in polluted fiords should be conducted on a sampling scheme that is matched to the seasonality of the main sediment sources. Our study also suggests that biogeochemical investigations must ascertain the frequency and magnitude of geological processes, such as turbidity currents, and thus, the need for multidisciplinary investigations. Toxic metals, such as lead, mercury and cadmium, could be reintroduced into the water column through the action of turbidity currents, and thus into the food chain, long after the burial of industrial waste products.

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REFERENCES

Buckley, D.E. and Winters, G.V., 1983, Geochemical transport through the Miramichi Estuary: Canadian Journal of Fisheries and Aquatic Sciences, v. 40, p. 162-182.

Dodimead, A.J. and Pickard, G.L., 1967, Annual changes in the oceanic coastal waters of the eastern Subarctic Pacific: Journal of Fisheries Research Board of Canada, v. 24, p. 2207-2227.

Farmer, D.M. and Freeland, H.J., 1983, The physical oceanography of fjords: Progress in Oceanography, v. 12, p. 147-220.

Farrow, G.E., Syvitski, J.P.M. and Tunnecliffe, V., 1983, Suspended particulate loading on the macrobenthos in a highly turbid fjord: Knight Inlet, British Columbia: Canadian Journal of Fisheries and Aquatic Sciences, v. 40, p. 273-288.

Lewis, A.G., 1976, The Biological Availabilty of Copper in Estuarine and Marine Environments: Final Report, INCRA Project No. 246, 115 p.

Lewis, A.G. and Syvitski, J.P.M., 1983, Interaction of plankton and suspended sediment in fjords: Sedimentary Geology, v. 36, p. 269-288.

Pickard, G.L., 1961, Oceanographic features of inlets of the British Columbia mainland coast: Journal of Fisheries Research Board of Canada, v. 18, p. 907-999.

Pickard, G.L. and Rodgers, G.K., 1959, Current measurements in Knight Inlet, British Columbia: Journal of Fisheries Research Board of Canada, v. 16, p. 635-678.

Prior, D. B., Bornhold, B.D., Wiseman, W.J., Jr. and Lowe, D.R., 1987, Turbidity current activity in a British Columbia fjord: Science, v. 237, p. 1330-1333.

Schafer, C.T., Cole, F.E. and Syvitski, J.P.M., 1989, Bio- and lithofacies of modern sediments in Knight and Bute Inlets, British Columbia:-Palaios, v. 4, p. 107-126.

Stone, D.P., 1977, Copepod distributional ecology in a glacial run-off fjord: Unpublished Ph.D. thesis, University of British Columbia, Vancouver, 256 p.

Sugai, S.F., 1987, Temporal changes in the sediment geochemistry of two southeast Alaskan fjords: Deep-Sea Research, v 32, p. 913-925.

Syvitski, J.P.M., 1991, Theory, Methods and Application of Particle Size Analysis: Cambridge University Press, New York, 374 pp.

Syvitski, J.P.M., in press, Fluvial sediments and marine interactions in Canada: An overview: Canadian Water Resources Journal.

Syvitski, J.P.M., Asprey, K.W., Clattenburg, D.A. and Hodge, G.D., 1985, The prodelta environment of a fjord: suspended particle dynamics: Sedimentology, v. 32, p. 83-107.

Syvitski, J.P.M., Burrell, D.C. and Skei, J.M., 1987, Fjords: Processes and Products: Springer-Verlag, New York, 379 p.

Syvitski, J.P.M. and Farrow, G.E., 1983, Structures and processes in bayhead deltas: Knight and Bute Inlet, British Columbia: Sedimentary Geology, v. 36, p. 217-244.

Syvitski, J.P.M. and Murray, J.W., 1981, Particle interaction in fjord suspended sediment: Marine Geology, v. 39, p. 215-242.

Syvitski, J.P.M., Smith, J.N., Calabrese, E.A. and Boudreau, B.P., 1988, Basin sedimentation and the growth of prograding deltas: Journal of Geophysical Research, v. 93, p. 6895- 6908.

Winter, D.F., 1973, A similarity solution for steady state gravitational circulation in fjords: Estuarine and Coastal Marine Science, v. 1, p. 387-400.

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