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James P.M. Syvitski

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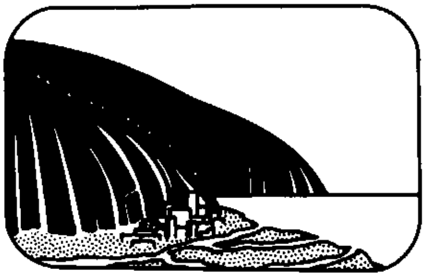


DNAG #2. Estuaries, Deltas and Fjords of Eastern Canada

James P.M. Syvitski
Geological Survey of Canada
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

Introduction

The science of land-sea interactions is of particular importance to Canadians. Canada is a country of geographic immensity with the world's longest coastline, the largest number of estuaries and deltas, and more fjords than all other countries combined. The geological study of these environments relates to one or more of the following global objectives:

(1) To cope with anthropogenic environmental problems: estuaries have historically been the prime disposal site for waste from Canada's coastal cities and industries;

(2) To understand the impact of paleo- and potential climatic conditions (usually involving high resolution stratigraphic investigation of well-dated cores);

(3) To comprehend the effect of past and future, including artificially-induced, sea level fluctuations; and,

(4) To document the key historical processes that have contributed to the development of the present environment, both from an engineering hazards point-of-view and from one focussing on the development of sediment facies models.

The excerpt in this issue, "Estuaries, Deltas and Fjords", is from the DNAG volume *Geology of the Continental Margin of Eastern Canada* being edited now by M.J. Keen and G.L. Williams. It comes from the chapter "Modern Sedimentation Processes" edited by C.L. Amos.

Estuaries

An estuary is defined here as a partially enclosed body of water which has a free connection with the open sea and in which the marine water is measurably diluted with the influx of fresh water from land drainage. Estuaries of eastern Canada are the result of: (1) drowning of river valleys incised during the low sea level period of the Late Pleistocene; (2) tidal cutting of glaciomarine sediment along presently emerging coastlines; (3) processes of glacial excavation common to fjord formation; (4) natural bedrock control and areas of active faulting; and (5) local environments that form along prograding coastlines, such as tidal inlets and lagoons. Sediment erosion, transport and deposition are related to the time-dependent and sometimes complex circulation patterns within the estuary. Estuarine circulation systems have been classified principally by the level of stratification within the water column (Bowden, 1967; Partheniades, 1972; Dyer, 1973; Kjerfve, 1978; Officer, 1983). The level of stratification is a simple balance between the buoyancy forces set up by inflowing fresh water and the processes such as those associated with tidal action that work to mix the fresh water with the denser and saltier sea water. The types of estuaries include: (1) salt wedge, where the river flow dominates with little mixing between the fresh-water and the salt-water layers; (2) two-layer flow with entrainment (e.g. fjords), where mixing processes across the interface become important; (3) partially-mixed, where river-flow buoyancy is balanced by tidal mixing; and (4) vertically homogeneous (well-mixed), where mixing processes predominate (see Figure 1). These ideal estuaries are usually further complicated by: the Coriolis effect that forces flow to the right in the northern hemisphere; centrifugal accelerations along the sinuous portions of inlets; the lateral separation of inflow and outflow currents as a result of complex bathymetry — multiple channels, for example; flow accelerations developed over rough bottoms and through inlet constrictions; pressure gradients developed in the atmosphere or the river, as a result of changing wind structure or freshwater discharge; surface mixing from strong winds; the breaking of internal waves; and isohaline instabilities developed during the process of salt rejection associated with sea-ice development.

There may be a variety of circulation patterns for a particular estuary, the patterns changing with place and time. For example, the St. Lawrence estuary varies seaward from a salt wedge to a partially-mixed, and finally to a fjord-type of estuary (d'Anglejan and Smith, 1973). The upper Miramichi estuary seasonally alternates between salt wedge when freshwater discharge is high, to a highly-stratified two-layer system when the discharge is low (Vilks and Krauel, 1982). River regulation can also cause radical changes in estuarine dynamics and kinematics. The control of the outflow of the Rivière aux Outardes allows tidal mixing to dominate the system; furthermore, regulation has enhanced the influence of ocean swell (Cataliotti-Valdina and Long, 1984).

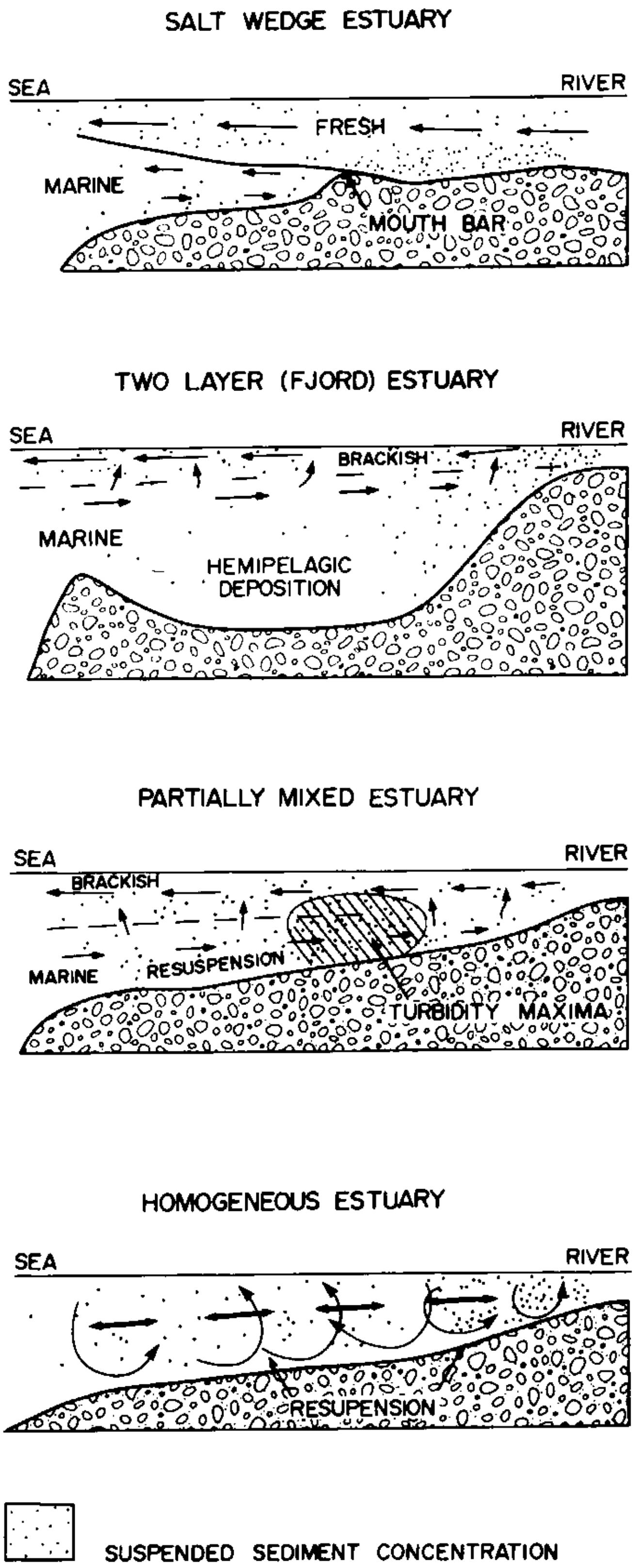
The effects of estuarine circulation on sediment movement are complex. Figure 1 shows the essence of the salient features. At the leading edge of a salt wedge, bedload material accumulates to form mouth bars or tidal bars. Dredging of these deposits may have to be semi-continuous to increase access to port facilities (Schafer, 1973). Hemipelagic sedimentation (i.e. sedimentation dominated by a vertical flux of particles) is commonly observed under fjord-estuarine circulation (e.g. lower St. Lawrence estuary; Syvitski *et al.*, 1983d). Hemipelagic particles include floccules, agglomerates of organic rich particles and zooplankton-egested fecal pellets; these are particle types that enhance deposition close to the river mouth (Lewis and Syvitski, 1983). Deposits include discrete alternations of sandy silts and organoclays (varves) reflecting the seasonality of snow storage and freshet release (e.g. Saguenay Fjord; Schafer *et al.*, 1983). Partially-mixed estuaries are commonly shallow and so their bottom sediments are reworked and resuspended. A zone of high suspended-sediment concentrations known as a turbidity maximum may form (e.g upper St. Lawrence estuary, Silverberg and Sundby, 1979; Miramichi estuary, Kranck, 1981). Mass balance calculations generally reveal a net export of sediment out of the partially-mixed estuary (e.g. Miramichi estuary; Winters, 1983). Homogeneous (well-mixed) estuaries, such as the Minas Basin within the Bay of Fundy, have extremely turbid waters due to tidal resuspension. Although bed load transport is more important in these well-mixed estuaries than in others, sediment is largely transported as a horizontal flux of suspended particles, principally controlled by the residual tidal current within the subtidal region (Amos and Long, 1980).

Many East Coast estuaries are fringed by intertidal marshes and mudflats. These are temporary or permanent depositional areas of special importance in estuaries of large tidal range on low-lying coastal plains. Examples include the St. Lawrence estuary, Rupert Bay and other estuaries along the east and west coasts of James Bay and Hudson Bay, the Koksoak and other river estuaries of Ungava Bay, and the bays and fjords along Frobisher Bay and Cumberland Sound.

Two particularly important factors affect sediment stability and mobility within all the estuaries of the Canadian East Coast and Arctic: (a) Rafting by sea ice redistributes shoreline sediment into deeper water. Discrete zones of ice-rafted material form in large estuaries (e.g. St. Lawrence estuary, Syvitski *et al.*, 1983d) and these may be recognized in older sediments (e.g. Minas Basin; Amos, 1978). Ice-rafting armours the more easily eroded estuarine sands and muds with a coarser-grained gravel component. (b) Benthic fauna substantially alter the physical properties of the substrate through bioturbation and bio-erosion (Syvitski *et al.*, 1983c). Effects include: (1) increased bed erosion through increased sea floor roughness and, consequently, near-bed turbulence; (2) resuspension of bottom sediments, directly through stirring or the egestion upward of turbid water, or indirectly through inducing changes in the sediments water content and particle binding, and so affecting the bed-shear stress needed for erosion; and (3) bioturbation that will transport sediments to and from the seafloor.

Figure 2 illustrates some of the key influences on estuaries within the Canadian East Coast and Arctic. They include the tidal range river discharge, runoff from land, zones of permafrost and areas influenced by glacial meltwater. Two areas have very high tides: (1) the Bay of Fundy (11 m mean tidal range); and (2) the region around Hudson Strait, including Ungava Bay (10 m mean tidal range). The Bay of Fundy has been well studied (e.g. Gordon and Hourston, 1983) and these studies show that at least headward it is a classical well-mixed homogeneous estuary. The region around Hudson Strait has received little attention, but with the exception of parts of Ungava Bay, thought to be well-mixed, nearby estuaries vary in type from partially-mixed to fjord. Regions of permafrost have a low capacity for ground water storage and, as a result, estuaries of these areas have rivers that are flood-dominated. The influence of such random discharge events on the dynamics of estuaries is not well understood, but such floods may be an important modifier of estuaries that fall within the zone of continuous permafrost typical of most of the Arctic. The runoff pattern varies systematically from one of desert conditions in the northwest Arctic to one of extreme runoff values toward the Atlantic Provinces, such as Newfoundland. Except for the Saint John River in New Brunswick, small drainage basins typify the Maritime Provinces and rivers hardly influence local estuaries. The Arctic Archipelago has both alpine ice fields and ice caps, so that the drainage basins are influenced by glacial meltwater. This meltwater, loaded with glacial rock flour, is typically very turbid, and this effluent results in high estuarine sedimentation. Figure 3 shows the main types of estuaries of the Canadian East Coast and Arctic.

Fjords are commonly silled and consequently sea level fluctuations during the Holocene have changed the estuarine style of circulation (Syvitski *et al.*, 1986). As an example, the Hamilton Inlet sill that partially encloses Lake Melville, was 80 m deep 7000 years ago, 50 m deep 5000 years ago and is 28 m deep now. This caused a gradual decrease in the bottom water salinity (by 5‰ (ppt)) in Lake Melville during the same period (Vilks and Mudie, 1983). Sea level fluctuations dramatically affected the estuarine circulation within the Bedford Basin, a Nova Scotian fjord (Miller *et al.*, 1982). The fjord, 8000 years ago, was a cold, brackish estuary that, with falling sea level, changed into a freshwater lake 7000 years ago. Sea level



SALT WEDGE ESTUARY

TWO LAYER (FJORD) ESTUARY

PARTIALLY MIXED ESTUARY

HOMOGENEOUS ESTUARY

GSC

Figure 1 *Simplified cartoons of the pattern of circulation and turbidity within the four principle types of estuaries found along the Canadian East Coast.*

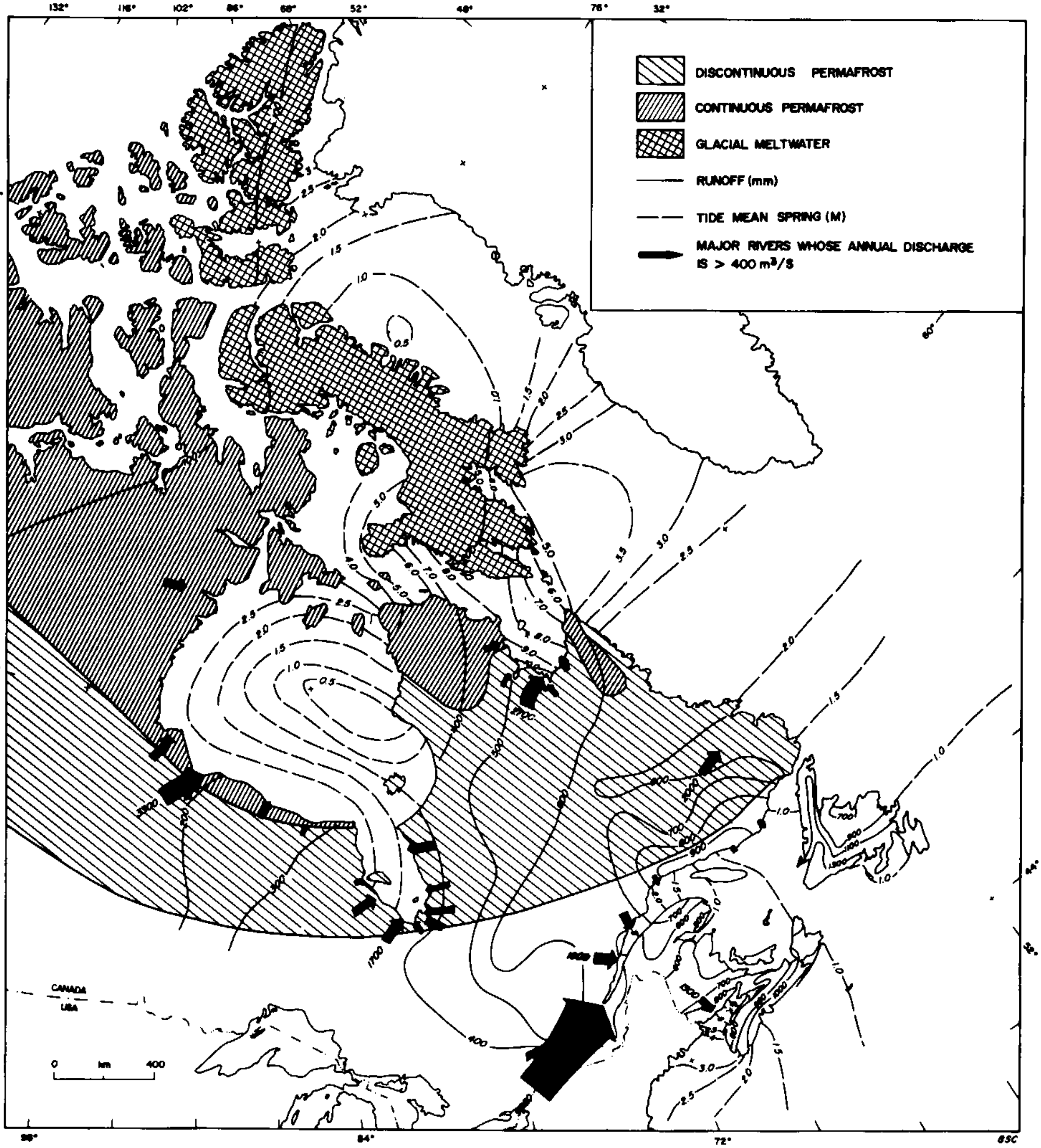


Figure 2 *Principle factors influencing estuaries within the Canadian East Coast and Arctic (see text for details). The mean annual discharge for the largest rivers is given at the rear of the proportional arrows (m³ s⁻¹).*

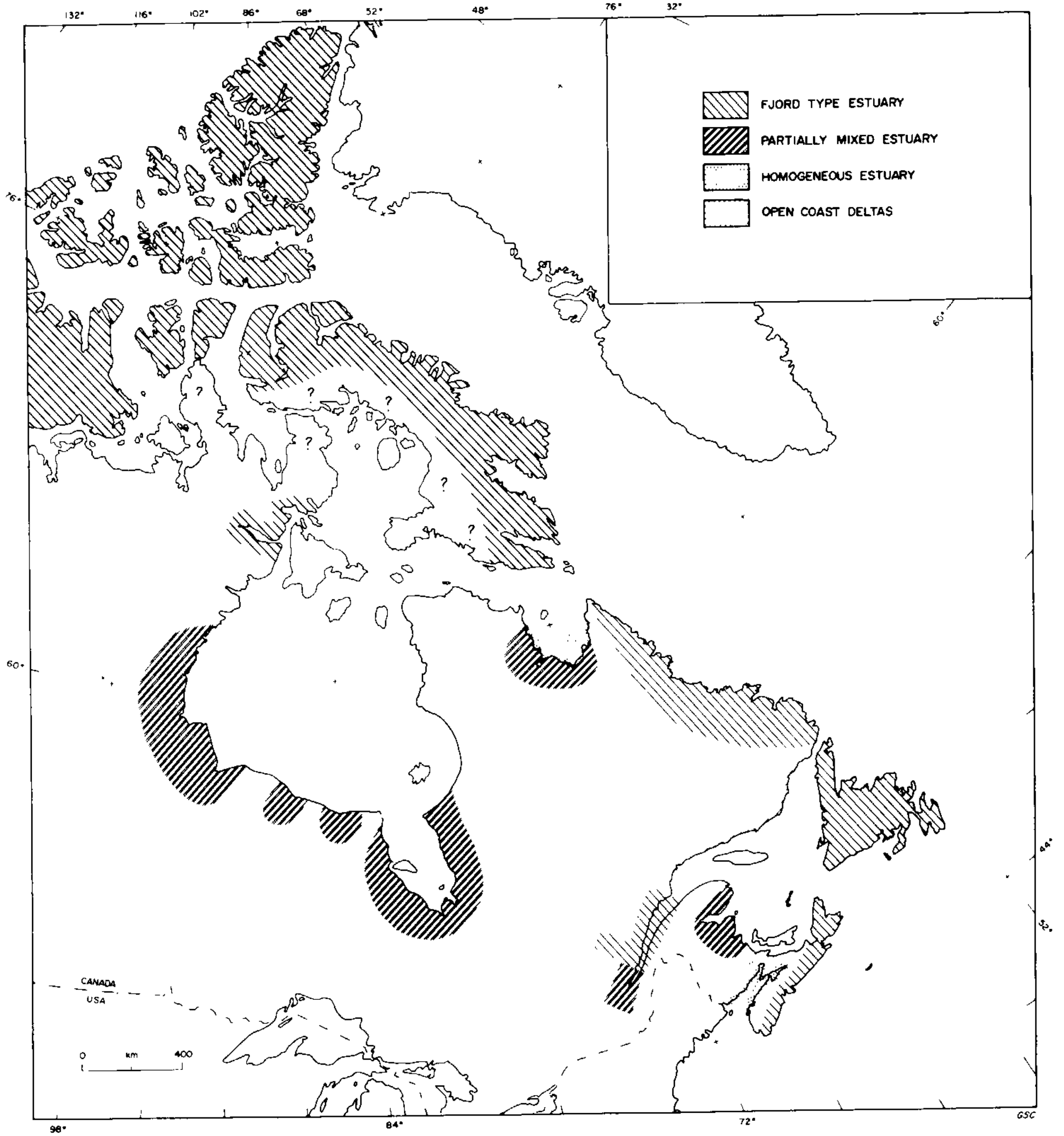


Figure 3 *The distribution of estuaries and deltas along the Canadian East Coast and Arctic.*

began to rise locally 6000 years ago, and a deep salt-wedge estuary was produced, and this trend continued to produce the present-day deep-silled estuary.

Deltas

Deltas are nearly flat alluvial deposits formed around the mouth of a river. They result from a radical change in the fluvial hydraulics as the river enters a standing body of water causing: (1) bed load deposition as part of the subaerial and intertidal topset deposit; and (2) subtidal sedimentation of the suspended load onto the subaqueous portion of the delta, the prodelta environment. A marine delta survives only if sediment supply and accumulation are greater than sediment removal by waves, tidal action, or longshore transport. During maximum growth, a delta can prograde beyond the normal coastline. The northern shore of the Gulf of St. Lawrence delta is the only major deltaic coastline in eastern Canada (Figure 3). Elsewhere along open coasts, the rate of removal is greater than the rate of supply, as it is, for example, in much of the James Bay, Hudson Bay and Ungava Bay (d'Anglejan, 1980, 1982). Two plausible reasons exist for this condition. First, bed load is a small percentage (10-30%) of the total sediment supply and composed of relatively fine-grained material (unpublished data from B. d'Anglejan). This sediment gives only limited structural stability for delta growth. Second, tidal action is capable of removing much of the suspended load away from the coastline. Canada's largest river, the St. Lawrence, is another example where these conditions are found. Exceptions include the deltas developing in front of rivers delivering large amounts of sands from proglacial deposits or from exposed moraines (e.g. Great Whale River); and those where a river mouth is protected from direct wave action and longshore transport (e.g. Nottaway River in Rupert Bay, Harricana River south of James Bay).

A number of fjord-valley rivers provide good examples of deltaic progradation on Canada's East Coast and Arctic. The reasons for this include: (1) the steeper river gradient — the thalweg — of fjord-valley rivers that gives a greater capacity for transport of coarse-grained bed load, which once deposited is not easily modified by tides and waves; (2) the enclosed nature of these long and narrow inlets, which provides an environment where longshore transport is negligible (Syvitski and Farrow, 1983); and (3) sedimentation being greatest near the delta on account of the very nature of fjords, containing as they do deep bodies of water with limited circulation below an estuarine layer (Farrow *et al.*, 1983)(see section on Fjords below). Fjord deltas can best be described as "Gilbert-style" deltas with topset, foreset and bottomset deposits. One particularly large delta has developed from the Churchill River that flows into Lake Melville, Labrador (a misnomer because the lake is actually a marine fjord; Vilks and Mudie, 1983). Most of the other large fjord deltas, however, are found at the heads of fjords of the east coast of Baffin Island, an area dominated by turbid glacial meltwater (Church, 1972; Knight, 1971; Syvitski *et al.*, 1983a). These arctic deltas are commonly referred to as sandurs (sand plain).

Sandurs differ from the deltas of lower latitudes because of the strong influence of periglacial processes within a paraglacial framework. The important periglacial phenomena include: (1) the transportation of most fluvial sediment in only a few days per season (Church, 1972); (2) large-scale aeolian transport on account of extreme winds and lack of vegetation which is limited only by the availability of finer-grained material (Gilbert, 1983); (3) substantial movement of glaciofluvial sediment (Gilbert, 1982); (4) structural armouring of deltaic tidal flats by boulders brought in by sea ice (McCann *et al.*, 1981; this process affects both subarctic and arctic tidal flats); (5) rock falls, slides and dirty avalanches released along fjord walls in association with the hydrofracturing process (Church *et al.*, 1979); and (6) rare but impressive transport of water and sediment due to a sudden discharge from ice-dammed lakes (jokolhlaups). A paraglacial framework refers to environments that have a greater than normal supply of fluvial sediment (Church and Ryder, 1972). Catchment basins having a "normal" denudation rate would transport and dispose of the same amount of material that is made available by weathering processes in the local basin. High sediment yields of the paraglacial environment are a result of the erosion of glacial, proglacial and isostatically raised fluviomarine sediment deposited during and after the last major ice advance. Many arctic sandurs were affected by a new paraglacial cycle at the onset of the Little Ice Age (circa A.D. 1700) further increasing the supply of sediment to the deltas.

Most of the deltas and estuaries of Canada's East Coast and Arctic have been affected by significant climatic shifts and changes in sea level during the Late Pleistocene and Holocene. One result has been pulsed deltaic prograding deposits, now found uplifted along emerging coastlines, and incised as a result of modern fluvial cannibalism. For instance, the Baffin sandurs commonly consist of: (1) major outwash deposits formed in front of rapidly ablating valley glaciers during the Hypsithermal period (4000-6000 years B.P.); followed by (2) deposits formed as a result of minor delta advances during the warmer stages of the generally cooler Neoglacial Period less than 4000 years ago (Church, 1978). For Ekalugad Sandur, for example, half of the annual sediment yield during the Neoglacial was derived from erosion of the isostatically uplifted Hypsithermal deposits (Church and Ryder, 1972).

Much research remains if we are to understand the pathways of sediment transport in subarctic and arctic estuaries and deltas. In particular, the following questions remain to be resolved: (1) what effect does a permafrost substrate have on estuary development and delta progradation? (2) how do long-term as opposed to short-term climatic fluctuations affect sediment yield and thus facies development in estuaries and deltas? (3) how do long-term oscillations in river discharge, and sea level fluctuations in estuaries and deltas, affect sediment stability in the short term? and (4) can the influence of sea level fluctuations be distinguished from those of discharge fluctuations when both have been important modifiers in the architecture of arctic deltas and estuaries? The last question may be the most elusive, for we must be able to decouple the effects of changes in discharge from the effects of changes in sea level even when we may not know if the two are in-phase or out-of-phase.

Fjords

Fjords are the deepest of all estuaries. Most are deeper than 200 m, many are deeper than 500 m and some are deeper than 1000 m. Circulation within the upper waters (30-50 m) is usually of the two-layer estuarine type and is related to river runoff, described already. Deeper water circulation (or lack of it) depends on sill depth, tidal mixing over the sill, and deep water renewal through periodic exchanges of denser shelf waters with waters of the fjord basin. Detailed references and reviews on the fjord literature can be found in Syvitski *et al.* (1986), Farmer and Freeland (1983), Syvitski and Skei (1983), Andrews and Matsch (1983) and Freeland *et al.* (1980). There are some 700 "classical" fjords along the Canadian East Coast and Arctic, so that their scientific importance can hardly be overstated, especially for the study of land-sea interactions.

Much of the sediment accumulation within these overdeepened coastal basins can be related to glacial/proglacial infilling during and just after the last Pleistocene ice advance. Paraglacial deposits may include: (1) a basal till complex (lodgement till, waterlain till, push and dump moraines); (2) proximal glaciomarine sediments dominated by thinly-bedded turbidites alternating with hemipelagic layers; (3) distal glaciomarine sediments that tend to be fine-grained and highly bioturbated; and (4) widely varying recent sediments that reflect non-glacial conditions within the east coast fjords of lower latitudes (south of 62°N), and the glacial conditions at the more northerly latitudes as a result of the Little Ice Age (circa A.D. 1700). A continuum exists between the most northerly fjords, dominated by ice, and the most southerly dominated by river discharge or wind. Consequently, the next sections describe the end members.

Arctic Fjords. The northern coast of Ellesmere Island has a number of "frigid" fjords

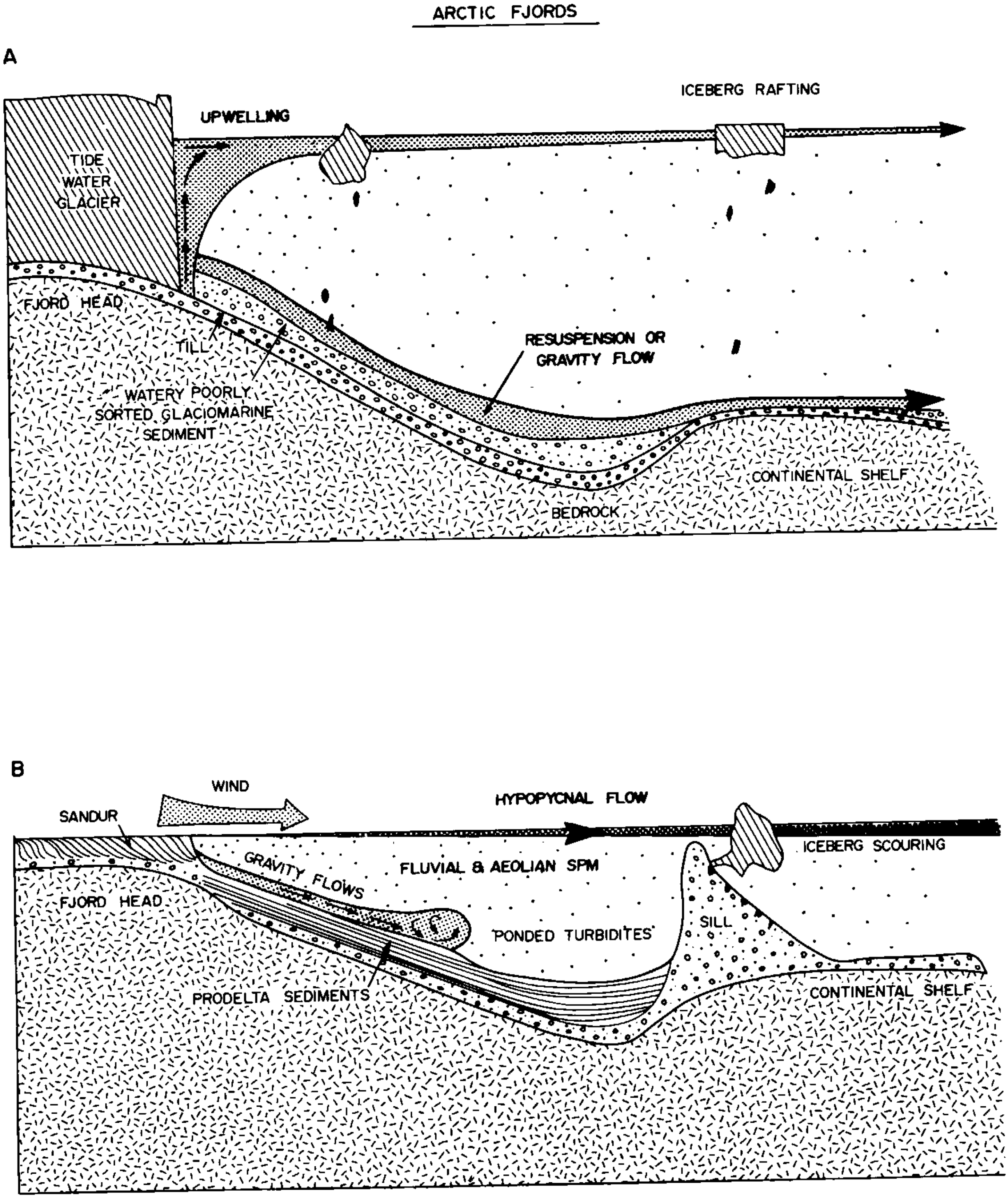


Figure 4 *Sedimentologic features associated with two Arctic fjord end members, dependent on the presence or absence of a tidewater glacier.*

that are both ice-covered year round and enclosed at their seaward margin by the Ward Hunt Ice Shelf. As an example, the waters of Disraeli Fjord (83°N) are composed of 45 m of freshwater (a consequence of the ice shelf) lying on top of 135 m of sea water (Keys, 1978). The permanent ice cover prevents mixing by wind, and as there is little tidal mixing either, a unique oceanographic condition is maintained. Meltwater from the tidewater glacier at the head of the inlet, sinks to the pycnoclinal interface where it spreads down the fjord, while continuously depositing glacial flour. The consequence is a low-energy seafloor environment containing highly-bioturbated silty clay.

Most other Arctic fjords undergo seasonal freeze and thaw of their sea ice. During the fall and winter, salt is released during the formation of sea ice and this may stimulate water-column mixing through the initiation of salt-driven circulation, even though wind-driven currents are prevented (Gade *et al.*, 1974; Perkin and Lewis, 1978). The melting of the ice cover during the spring, accompanied by freshet runoff, re-establishes stratification, which in turn deteriorates throughout the summer through highly effective wind-induced mixing (Nielsen and Ottesen-Hansen, 1980). The lack of long periods of stratification in the water column has two effects on the patterns of local sedimentation: (1) hemipelagic sedimentation is especially high near river mouths; and (2) relatively stronger bottom currents lead to sediments being ponded and "plastered" in basins and slopes, rather than being "quietly" deposited as a conformable cover from an extended surface plume. Sea ice is also an important sedimentological agent in most arctic fjords. The ice passively carries fluvial, aeolian and colluvial material to be subsequently released from the ice during break-up (Berthois, 1969; Knight, 1971). In addition, sea ice actively incorporates sediment during winter freezing along the shores (Aitken and Gilbert, 1981).

Many Canadian Arctic fjords are influenced by processes associated with tidewater glaciers and icebergs. In both cases, melting below the waterline can inject significant amounts of fresh water into the fjord. Upwelling around icebergs can increase mixing and thus destabilize the estuarine circulation. Melting near the wall of a tidewater glacier continues year round and so contributes to the maintenance of surface stratification (Matthews and Quinlan, 1975; Greisman, 1979). Sedimentation is highest near the fronts of tidewater glaciers with rates commonly being about one metre per year and the resulting deposits are poorly sorted and have a high water content (Gilbert, 1982). Sediment instability may lead to creep down the proximal slopes of the fjord and deformation of strata (Syvitski *et al.*, 1983b). During the calving of icebergs, the seabed may be disturbed, and the huge flood waves generated — "Tagsaq" — can wash material far above the high tide line (Petersen, 1977). A drifting iceberg may remain stable for several days while continuously releasing sediment from the submerged portion of the berg. More rapid melting below the waterline eventually changes the centre of gravity of the berg which overturns and breaks up. Under such conditions, surface sediment which has been concentrated through melt-out is dumped (for details on iceberg rafting see Ovenshine, 1970). Icebergs may become grounded in shallow portions of fjords, such as prodelta slopes and sills with depths less than 200 m, reworking the seafloor during the grounding process, and contributing sediment to the seafloor during their period of immobility and ablation (Blake, 1977; Vorndran and Sommerhoff, 1974).

Where the glaciers are subaerial, sandur deltas rapidly develop (see section on Deltas above). Where these deltas are actively prograding, the prodelta slopes are crossed by erosive gravity flow channels. 1-5 m deep, 20-100 m wide (Syvitski *et al.*, 1983b). These prodelta channels may coalesce in deeper water (Syvitski and Farrow, 1983). Their shallow water position appears controlled by the position of a sandur's flood channels. Most of the annual bed load is transported in a period of a few days during freshet conditions (Church, 1972). This leads to high sedimentation on the foreset slopes as steep as 15°-35°, with sediment instability and triggering of subaqueous channel activity as a result (Gilbert, 1983).

Recent deposits within the basins of Arctic fjords are volumetrically dominated by bioturbated hemipelagic mud. They also contain significant interlayers of turbidite and grain flow sands and occasional gravels (Gilbert, 1983). Some areas contain debris slumps generated from side-entry glaciofluvial sources and tributary fjords. A number of the fjords have significant submarine channels (up to 20 m deep, 300 m wide and 40 km long) which may indicate the occurrence of rare but powerful turbidity currents. Figure 4 gives the salient features of the end members of two Arctic fjords. Research into the sedimentology of these fjords is presently receiving international attention (Syvitski and Schafer, 1985; Syvitski, 1984; Syvitski and Blakeney, 1983; Powell, 1981; Elverhoi *et al.*, 1980; Lavrushin, 1968).

Wave-dominated Inlets. The second largest class of fjords on the East Coast of Canada after Arctic fjords includes those where sedimentation is low and waves dominate. Such fjords have one or more silled basins, only rarely more than 100 m deep, the exception being the deeper basins of Newfoundland fjords. These inlets result from lowland continental glaciation over coastal areas of resistant bedrock. Their dominant features have been recently summarized by Piper *et al.* (1983).

Wave-dominated fjords receive only 5-25% of their Holocene sediment fill from rivers; almost all the remainder is derived from waves reworking older marine sediment or glacial till (Piper *et al.*, 1983). Sediment accumulation rates range from 0.5-3.0 mm yr^{-1} (between 1 and 4 orders of magnitude less than the rates in arctic fjords). The highest sedimentation rates occur in deep basins which are adjacent to shore areas subject to the greatest wave intensity. The larger waves arrive as open-ocean swells or storm waves. Cliff retreat of coastal exposures of glacial sediment may have rates that exceed 1 m yr^{-1} near the fjord mouths decreasing to 0.25 m yr^{-1} in exposed areas of the inner fjord.

Sediment supply to fjords is variable. In areas subject to marine transgression, wave-cut platforms develop through the erosion of till cliffs, such as drumlins, and the platforms are gradually submerged by rising sea level (Barnes and Piper, 1978). The platforms are armoured with gravel, the basin slopes are a mixture of gravel, sand and mud, and adjacent basins are predominantly muddy. In areas of marine regression, proglacial and earlier Holocene sediments are eroded as they come within the zone of wave erosion with the falling sea level. The sediment distribution in these areas is similar to the wave-dominated inlets where sea level is rising.

Severe storms are capable of erosion and resuspension of sediment found in water depths of many tens of metres, up to 70 m on the northern exposed slopes of the lower St. Lawrence estuary, for example (Syvitski *et al.*, 1983d). After the storms, suspended sediment concentrations remain high for many days in a layer near the bottom (Delure, 1983; Barrie and Piper, 1982). Fine sand and silt settle out rapidly, leading to the deposition of thinly-banded graded layers on the basin floors (Letson, 1981). The time interval between these layers, measured in cores, suggests that the storms associated with them have a recurrence interval of 20-50 years. Between these major storms, hemipelagic and ice rafted sediments accumulate on the basin slopes (Piper *et al.*, 1983).

Acoustic surveying can be used to distinguish wave-dominated fjords from those dominated by rivers or tides. Wave resuspension results in onlapping basin-fill units (Figure 5), rather than conformable, ponded or wedged units typical of other depositional settings (Barrie and Piper, 1982; Piper *et al.*, 1983). The complex distribution of sediment facies, that reflect bathymetry, fetch direction and wave-sheltered zones, is also diagnostic (Slatt, 1974; Stehman, 1976).

Fluvial-dominated Fjords. Although river-dominated fjords are perhaps the most widely studied of all fjord systems, both theoretically and experimentally, they are not a prominent physiographic type on the East Coast of Canada. The Saguenay Fjord and Lake Melville are two exceptions; large rivers enter both. The Saguenay River drains an area of about 78,000 km² and has a long-term mean an-

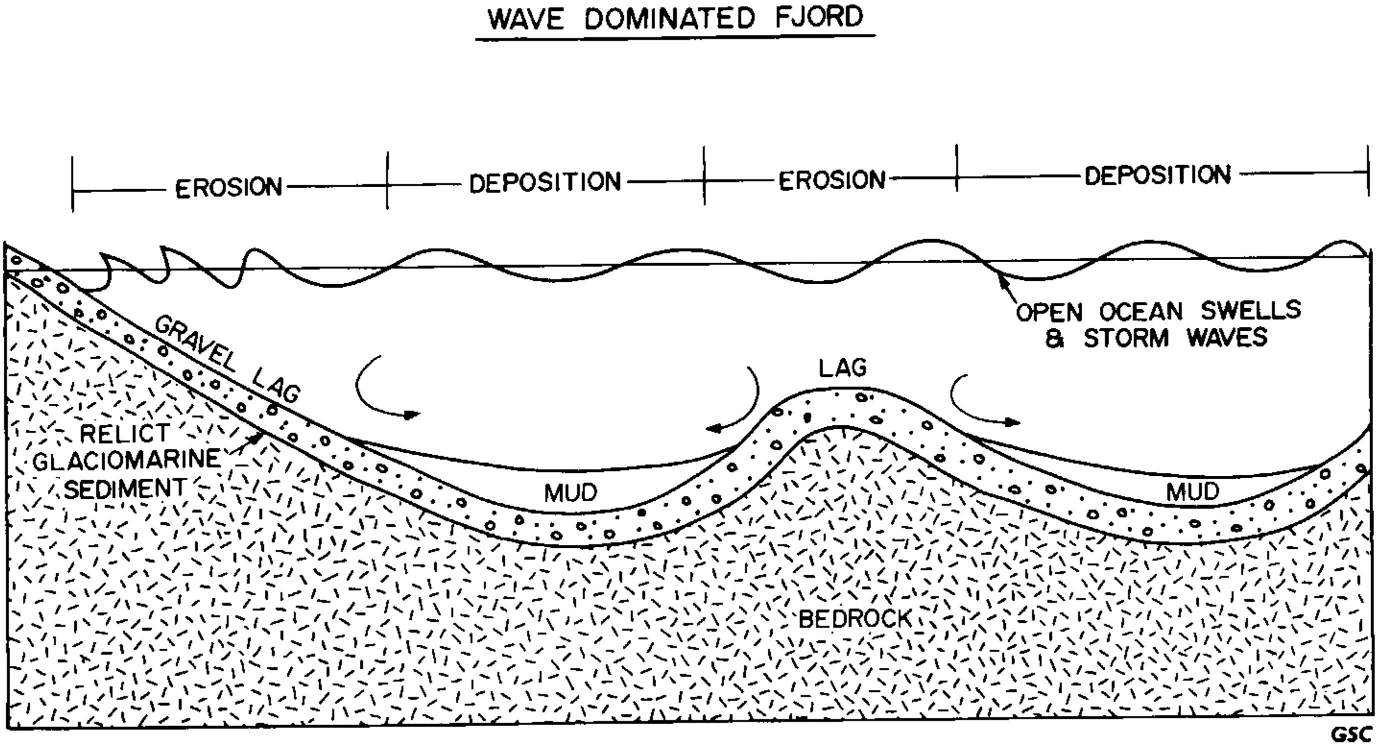


Figure 5 *Sedimentologic features associated with wave-dominated fjords.*

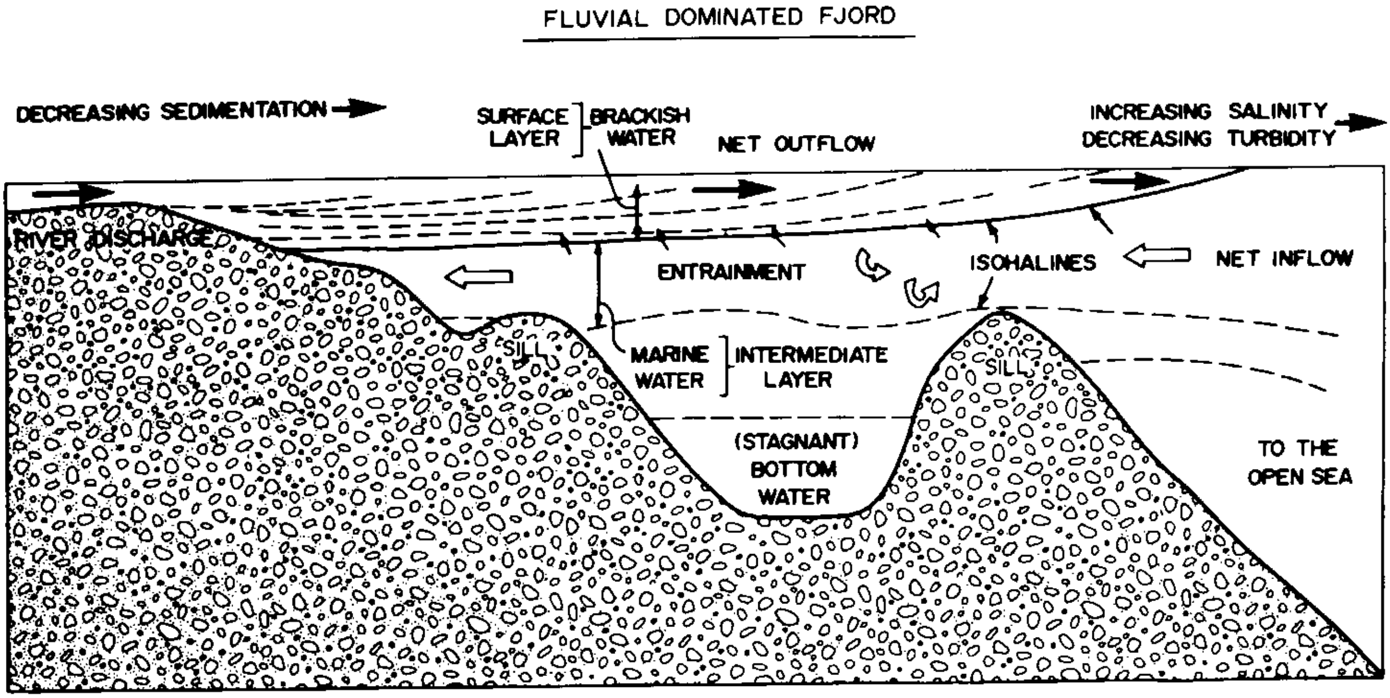


Figure 6 *Salient processes associated with a fluvially-dominated fjord.*

nual discharge of 1600 $m^3 s^{-1}$. The Churchill River that feeds Lake Melville drains an area of 92,500 km^2 with a long-term mean annual discharge of over 2000 $m^3 s^{-1}$. Both rivers are presently regulated. Predominantly, they transport older marine and periglacial sediments, eroded from raised terraces, during periods of high runoff when reservoirs are high.

Freshwater discharge into a fjord-like basin with thermohaline stratification is known as "buoyant hypopycnal flow". In this case two zones dominate the fjord (McClimans, 1978; Syvitski *et al.*, 1985): a proximal zone (upper prodelta) in which the energy of the river discharge controls the spreading and mixing of the plume with the surrounding basin water; and a distal zone (lower prodelta) where external agents control transport and mixing. Those external agents include tidal currents, wind, shoreline morphology and the earth's rotation. Mixing between water masses often occurs across sharp, well-defined pycnoclines.

Accumulation of freshwater near the river mouth creates a hydraulic head and the effluent effectively flows downhill (baratropically) toward the sea (Figure 6). As the surface water flows seaward it accelerates and entrains sea water into its outflow. Surface layer turbulence arises initially from river flow instabilities, followed by interlayer friction-induced turbulence and wind-induced surface turbulence. "Entrainment" is the process of nearly one-way transport of fluid from a less turbulent to a more turbulent region. The effects of entrainment and plume acceleration balance to maintain a nearby uniform thickness of the surface layer along the fjord. As saline water is entrained into the outward flowing surface layer, new seawater must enter the fjord at depth. The return or compensating current is in turn driven by a reverse internal pressure gradient (baroclinic flow).

Temperature and salinity are considered conservative properties of water and vary linearly with seaward distance as the surface layer mixes with ambient basin water. The concentration of suspended particulate matter is non-conservative because suspended particles settle under the influence of gravity. Larger suspended particles in particular behave non-conservatively, while slow-settling fine particles may mix more conservatively. This results in changes in the concentration of suspended particulate matter, with depth within the zone of estuarine circulation, and with distance from the river mouth. The pattern is expressed in a two-stage exponential function for each depth (Syvitski *et al.*, 1985). The down-fjord sedimentation rate appears to similarly decrease exponentially with distance from the river mouth. For example, Smith and Walton (1980) showed that sedimentation rates in the Saguenay Fjord diminish exponentially from 23 mm yr^1 near the river mouth to 0.4 mm yr^{-1} in the deep outer basin.

The accumulation rate, A, of sediment into the seafloor can be given as $A = Z + B - E$, where Z is the hemipelagic vertical flux; B is the sediment accumulation due to input from aeolian sources, bed load transport, mass movement and sediment gravity flows, ice rafting, flotation and deep water exchanges; and E represents periods of net erosion. The Saguenay Fjord is an excellent example of a situation where A equals Z. High sedimentation rates and high content of organic matter within the Saguenay system also lead to a concommittant reduction in ambient dissolved oxygen content in bottom and interstitial waters. As a result there is little bioturbation and detailed resolution of stratigraphic events is possible (Smith and Walton, 1980; Schafer *et al.*, 1980; Smith and Ellis, 1982; Schafer *et al.*, 1983). The lack of bioturbation has prevented the destruction of marine varves — the alternation of the organo-clay winter layers with summer sandy silts. The characteristics of the sediment within the summer layers, dated using ^{210}Pb, have been compared to historical discharge records of the main fjord-valley river. The results satisfactorily show that sand modal size can be used to predict freshet discharge levels (Schafer *et al.*, 1983). Figure 6 is a schematic cartoon of the salient processes in a fluvially-dominated fjord.

Future research topics on modern processes in fjords should include both general surveys and specific experiments. High-resolution surveys need to be conducted in the tide-dominated fjords of Frobisher Bay and Cumberland Sound, the iceberg-dominated fjords of eastern Ellesmere Island, the frigid fjords with permanent ice-cover of northern Ellesmere Island, and the fjords of the western Arctic Archipelago, many of which were ice free during the last major ice advance (circa 17,000 years B.P.). Of particular interest would be to compare styles of submarine slope failures within fjords having low to negligible earthquake activity with those of high seismicity such as Baffin Island and the Saguenay. Monitoring experiments might include: (1) inducing failure along the steep fjord-delta foresets to study variations in gravity flow processes and products, and the possible natural mechanisms normally responsible for such failures; (2) monitoring the separation of bed load and suspended load during peak arctic discharges with a view to studying facies development; and (3) monitoring the contribution of aeolian and ice-rated sediment to the seafloor using sediment traps.

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