Turbidity Current Activity in a British Columbia Fjord

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A year-long monitoring program within an elongated channel-fan system in Bute Inlet of British Columbia, Canada, detected active sand-transporting turbidity currents. Measurements of bottom velocities and sediment collected in traps, as well as damage to moorings and equipment, captured the signatures of frequent energetic events. Maximum calculated velocities achieved were 335 centimeters per second, with flow thicknesses of more than 30 meters. Coarse sand was transported at least 6 to 7.5 meters above the sea floor. Turbidity currents flowed a minimum distance of 25.9 kilometers, but possibly as far as 40 to 50 kilometers, over bottom slopes of generally less than 1°.

TURBIDITY CURRENTS, FLOWS OF sediment-laden suspensions, have been observed in freshwater lakes (*1*), but their occurrence in the world's oceans has been inferred largely from indirect evidence. Turbidity currents have been interpreted from cable breaks (*2*), diagnostic sea-floor morphology or acoustic images (*3*, *4*), and turbidite sequences on fans and in ocean basins (*5*). Using long-term instrument installations, close to the sea floor in a fjord, we have collected new data on these phenomena.

Frequent energetic sand-transporting bottom flow events were detected by current meters, tilt meters, flow deflection vanes, and sediment traps. The instruments were deployed, beginning in October 1985, at three locations along the axis of Bute Inlet, British Columbia, in water depths of 270, 425, and 520 m. Measurements were made within a well-developed sand-floored channel incised into Holocene fjord-bottom silts and clays, where acoustic imagery and sediment samples had indicated the likelihood of active channelized flows (*6*).

Bute Inlet, one of the deepest fjords in British Columbia, has a delta complex at its head supplied by the Homathko and Southgate rivers (Fig. 1). The Homathko sediment load is composed of 15% gravel, 65% sand, 15% silt, and 5% clays (*7*). Occasional large-scale discharge events are associated with spring snowmelt or lake outbursts (*8*). During the experiment a freshet flood reached 1630 m^3/sec. Floods also introduce large quantities of organic debris, trees, and limbs, some of which sink to the sea floor.

High-resolution acoustic surveying revealed an underwater channel-fan system on the fjord floor (*6*) (Fig. 1). Two subaqueous channels begin within the fjord head delta immediately seaward of the rivers' mouths. The delta-front slopes have been unstable, and there is evidence of rotational sliding and erosional gullying. At 150 m the delta-front channels coalesce into a single highly sinuous channel with terraced walls, degraded by localized sidewall instability (Fig. 2). Between 150 and 430 m, the channel is incised 25 to 30 m into the sea floor. Thereafter the depth of incision declines gradually downfjord. Depositional features such as outer-bank spillover lobes of sand begin at 430 m, and between 530 m and 600 m there is a complex lobate depositional area composed of overlapping low-relief distal lobes and abandoned, partially filled channel remnants. Distal sand splays occur on the fjord floor between depths of 600 and 620 m (Figs. 1 and 3). The entire depositional area comprises an elongated fan with overall geometry controlled by basin shape.

The longitudinal profile along the channel axis (Fig. 3) reveals that the steepest channel floor gradients are within the delta front (2.86°), generally declining downfjord. The incised channel has an axial gradient of 1.64°

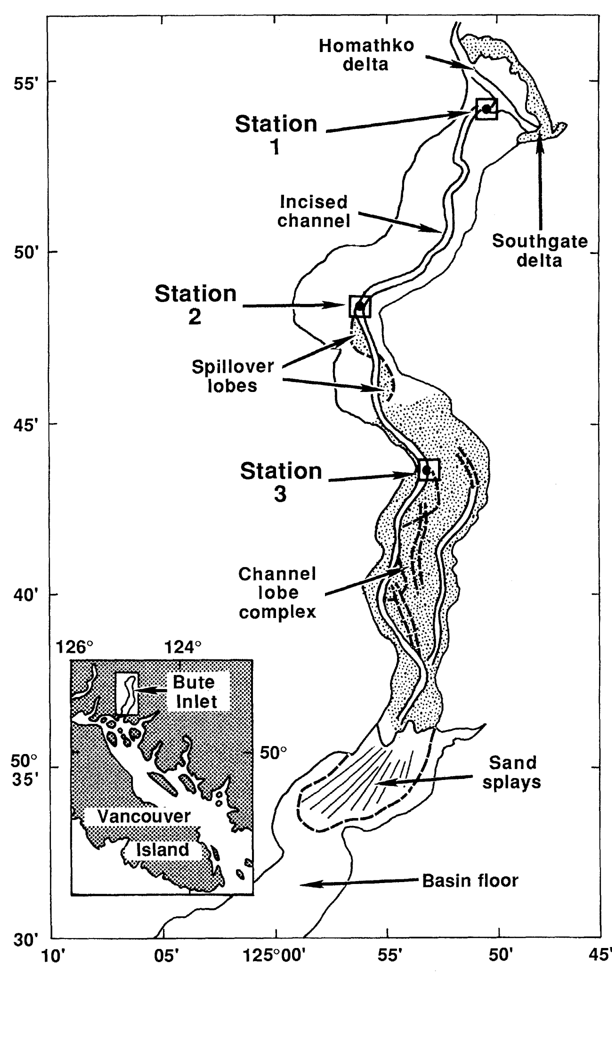

Fig. 1. Morphology of the Bute Inlet channel system and locations of monitoring stations.

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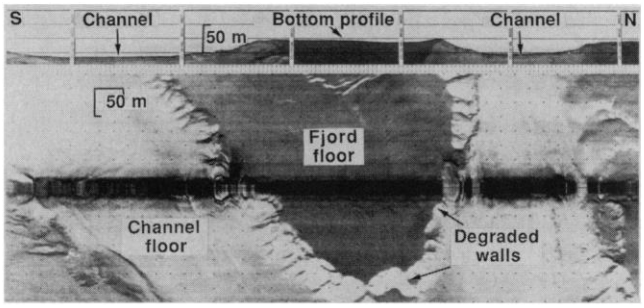

Fig. 2. Side-scan sonar image (100 kHz) of part of a channel bend where it is incised 25 to 30 m into the fjord floor.

to 0.56°, but through the principal zone of spillovers and depositional lobes the channel gradient ranges from 0.58° to 0.46°. The outermost lobe front is relatively steep (0.81°), whereas the distal sand splays occur where gradients are about 0.1° to 0.2°. The entire length of the channel axis from the delta front to the beginning of the distal splays is 42 km.

Moorings were placed within the channel at three stations (Figs. 1 and 3) at channel thalweg distances of 16.1 km and 9.8 km apart. The average along-channel gradient between stations 1 and 2 was 0.71° and between stations 2 and 3 was 0.58°. Mooring sites were selected from side-scan sonar imagery and 3.5-kHz profiles, and positions were fixed by acoustic ranging to the surface vessel, located by shore-based trisponders. Side-scan surveys also recorded mooring positions relative to bottom features; in these surveys transponders visible on side-scan sonar swaths were used. Each mooring consisted of an anchor (590 to 725 kg), basal acoustic release, and wire to floats 50 to 200 m above the sea floor. Aanderaa current meters (set to record average velocity over 20-minute periods and one instantaneous velocity every 20 minutes) were mounted 4 m above the sea floor. Anderson-type automatic sediment traps (*9*) were positioned with intakes 6 to 7.5 m above the bottom. Six vane-type deflectors with internal clocks, set to record time and date when deflected by an instantaneous current velocity of 50 cm/sec or greater, were placed at intervals up the mooring wire to a maximum height of 32 m off the channel bottom. The moorings were installed in October 1985 and serviced twice (February and June 1986), with final retrieval in November 1986.

Data from the moorings showed that turbidity currents occur frequently in Bute Inlet. The principal period of active currents was from spring through early winter, with a conspicuous lack of events from January 1986 to early May 1986. The data also suggested two different frequency and magnitude scales: frequent low-velocity, limited-distance flows and relatively infrequent large-scale events that travel long distances at high velocities.

Localized low-velocity events were detected at station 1 near the delta front, but these events apparently did not extend downfjord to stations 2 and 3. For example, at station 1 on 4 May 1986, down-channel currents recorded by Aanderaa meters exceeded 6.0 cm/sec for 160 minutes, reaching a peak velocity of 19.8 cm/sec. The flow did not deflect vanes set for a 50-cm/sec threshold. No comparable currents occurred at stations 2 or 3 on that day or immediately after, even though subsequent data taken in late May showed that equipment at all three stations was functional on 4 May.

By comparison, large-scale events affected all three moorings sequentially on at least three occasions (in mid-October 1985, late May 1986, and early July 1986), involving minimum flow distances of 25.9 km. Bottom features such as channel bedforms, erosional scours, and flutes strongly suggest that these flows originated within the delta and extended well beyond station 3, perhaps as far as the distal splay region, an along-channel distance of 40 to 50 km.

The times of arrival of flows at stations 1, 2, and 3 were detected by both current meters and vane deflectors. In our calculations of minimum average velocities from station to station we assumed that at least the near-bottom parts of the flows followed the sinuous channel axis.

A large-scale flow took place on 25 to 26 May 1986, coinciding with an unusually heavy snowmelt flood from the Homathko River. On 25 May discharge increased (from 172 m^3/sec on 24 May) to 797 m^3/sec, peaking at 1630 m^3/sec on 26 May. Figure 4 shows part of the Aanderaa current meter record at station 1 for 24 to 26 May, during which several velocity events occurred. Maximum velocities recorded by the current meter were relatively low (20.5 cm/sec maximum) and were not consistent with the vane deflection data. Since the meter had been on station for approximately 3 months, it may have sustained some damage. The bottom flow, which passed station 1 late on 25 May, deflected vanes to 27 m above the sea floor, exceeding velocities of 50 cm/sec to that height. Nevertheless, the Aanderaa data provide a record of times of occurrence of flows and associated fluctuations in water temperature and salinity (Fig. 4). The data from station 1 show that velocity pulses were accompanied by temperature reductions and slightly lagged salinity reductions; these data suggest the mixing of relatively fresh, cooler river water with fjord bottom water.

At 0945 hours on 26 May a flow exceeding 50 cm/sec deflected a vane 32 m above the sea floor at station 1. At 1105 hours, vanes were deflected to a height of at least 27 m above the channel floor at station 2. At 1443 hours, the flow arrived at station 3 but deflected only one vane at 7 m above the

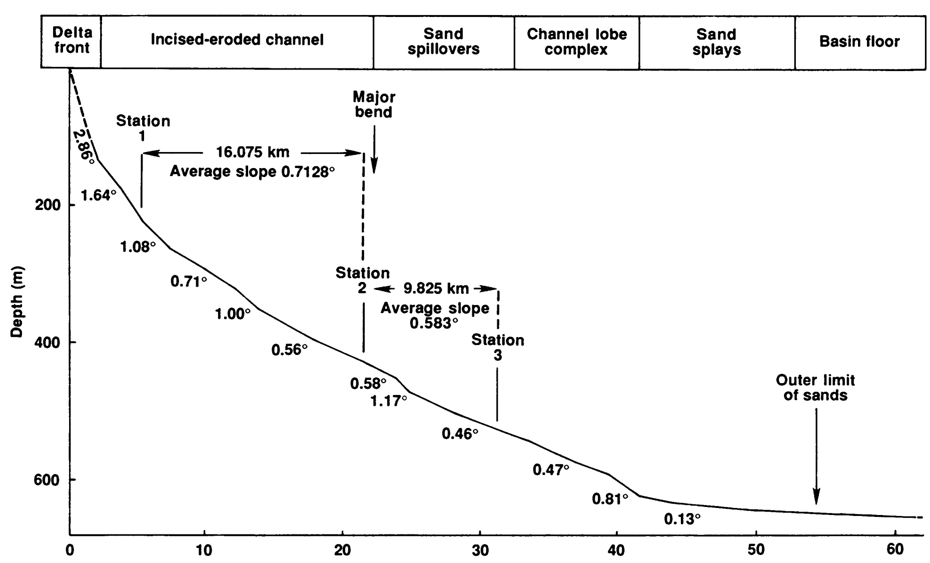

Fig. 3. Longitudinal profile along the sinuous channel axis from the delta front to the basin, showing the locations of monitoring stations.

bottom. These arrival times indicate flow velocities of 335 cm/sec between stations 1 and 2 and 75 cm/sec between stations 2 and 3. The flow velocities were highest in the incised channel between stations 1 and 2 and declined dramatically between stations 2 and 3. This velocity decrease and apparent thinning of the flow between stations 2 and 3 occurred where spillover lobes on outer channel bends indicate flow stripping and sediment deposition, both of which would reduce overall flow velocity.

Additional insights into the periodicity and scale of the turbidity currents are given by the sequences captured in the sediment traps. Generally, slow settling of suspended sediment from surface plumes (which were observed emanating from the delta) results in thin depositional units dominated by fine silts and clays with organic materials. By comparison, high-energy bottom currents give rise to sand transport.

During the flows of 25 and 26 May, coarse sand and muddy sand filled the uppermost 90 cm of the trap at station 1 (tube diameter, 3.45 cm), superimposed on 12 cm of fine organic muds deposited during winter and early spring. At station 2 (tube diameter, 2.15 cm) fine sands with mud filled the trap, apparently representing a fining of the sand component with increasing distance downfjord from the delta source. The traps at station 3 (tube diameter, 2.15 cm) provided a record of slow suspension settling (3 to 4 cm over the period February through May) with a superimposed layer (18 cm thick) of muddy fine sands with organics. The sediment traps at stations 1 and 3 (the station 2 trap was lost) for June through November 1986 also contained discrete sand units interlayered with fine muds. At station 1 there were massive intervals of quartz-diorite sands up to 47 cm long and graded fine to coarse sand layers (up to 10 cm thick) separated by thin mud layers (1.5 to 2.5 cm). At station 3 graded fine sands 30 to 40 cm thick were separated by discrete mud layers (up to 15 cm). Timing markers in the traps indicated mud deposition rates of 2 to 5 cm per 2 weeks, perhaps due to rapid settling of mud advected during the turbidity flows.

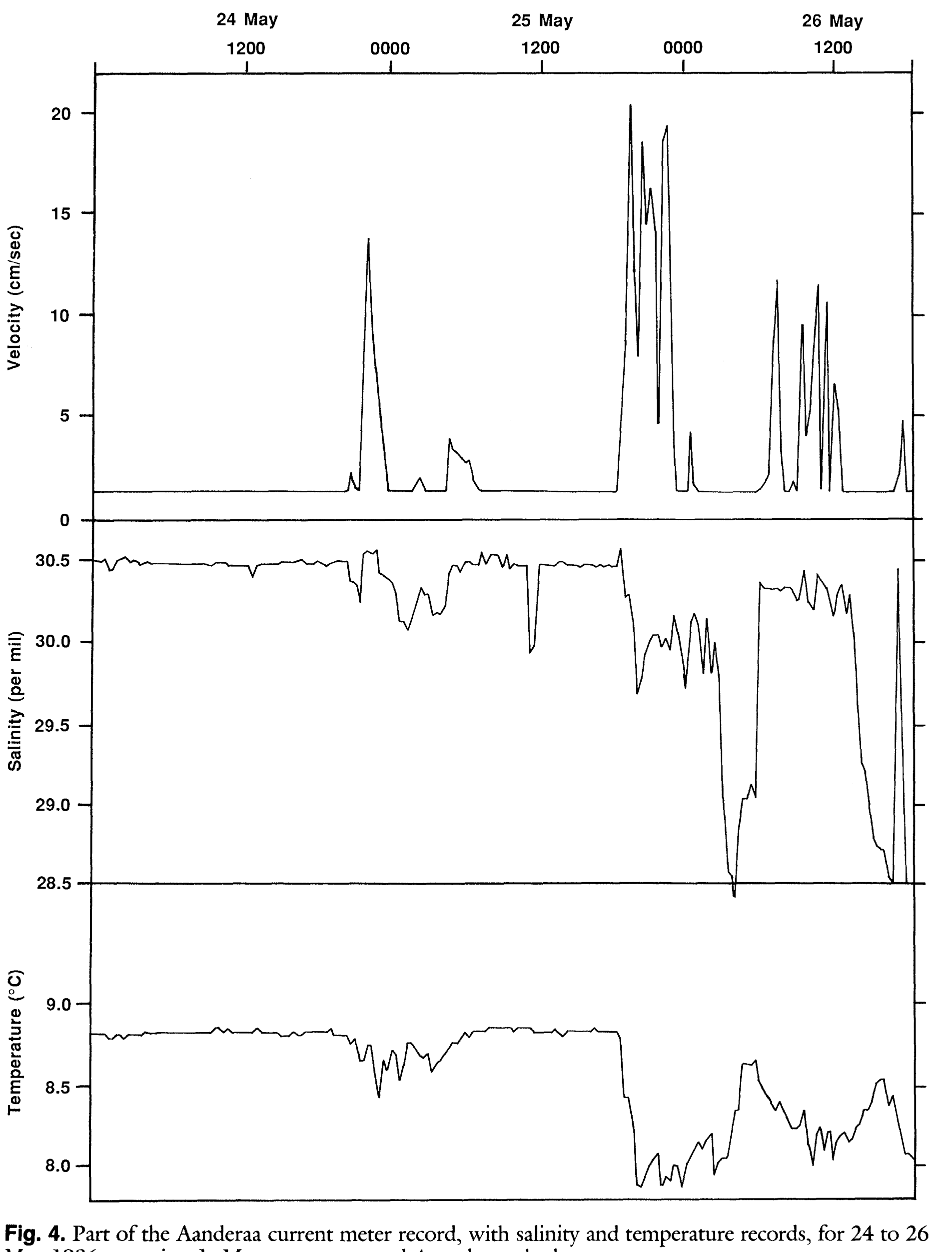

Fig. 4. Part of the Aanderaa current meter record, with salinity and temperature records, for 24 to 26 May 1986 at station 1. Meter was mounted 4 m above the bottom.

Because the magnitudes and frequencies of flows were unknown prior to the experiment, there were uncertainties about how to design the equipment and moorings. Dramatic evidence for the occurrence of high-energy events was also provided by difficulties with mooring retrieval and by damage unrelated to normal mooring operations or corrosion. On two occasions (February and May 1986) acoustic releases at stations 1 and 2 failed to detach the moorings. Subsequent recovery revealed coarse sand fouling the release mechanisms.

Relocation of the moorings showed that on three occasions entire mooring systems had been displaced downfjord along the channel. For example, between February and May 1986 station 1 moved from a mid-channel position to the inner edge of a bend, a distance of 200 m. From May to November 1986 station 3 moved from mid-channel a distance of 890 m toward the outer side of a bend. During the same period station 1 was heavily damaged. Mooring wire (3000-kg test) parted just above the anchor, allowing instrument packages to float free.

Instruments on the moorings experienced various degrees of damage. Rotors and vanes on the current meters were broken off, shackles and stainless steel frames and bands were bent and sheared, and in extreme cases entire instrument systems were lost. Some of the heavy damage appears to have been caused by impact from sunken trees and logs swept along by bottom currents.

On a less catastrophic level, sand particles lodged on equipment components and antifouling paint was severely abraded and stripped. Magnetite sands coated current meter magnets, and tree limbs sometimes were caught in the mooring hardware and rotors.

Equipment damage reduced data quality and continuity after impact during individual events. Fouling of Aanderaa rotors resulted in severe undermeasurement of current velocity, especially when compared to station-to-station calculations.

Several conclusions may be drawn from these experiments.

1) Over a relatively short monitoring period turbidity currents were active in Bute Inlet at various scales; these events resulted in channelized sand transport over low bottom gradients and long distances.

2) Individual flow events exhibited downfjord reduction in velocity and thickness but were sufficiently energetic to carry fine sands 40 to 50 km to the basin.

3) Flow thicknesses exceeded channel depth, both where the channel is deeply incised and on the outer bends of the channel below station 2. Between stations 1 and 2 the basal parts of the flow are channel confined, but upper levels may occupy the entire fjord floor, much in the manner indicated by Hay *et al.* (*4*).

4) Suspended sediment concentration (ρ) associated with the thickest parts of flows can be estimated from

$$CU^2 = g(\Delta\rho/\rho)h \tan B$$

(U is velocity, C is the drag coefficient, h is thickness, g is acceleration caused by gravity, and B is bottom slope). If C is 0.003, the average sediment concentration through the flow thickness is 12 g/liter. But this value is extremely sensitive to the drag coefficient. If C is 0.075 (*10*), the concentration is about 200 g/liter.

5) The factors responsible for the initiation of flow are not yet fully understood. The delta front is periodically unstable, and landslide generation of the turbidity currents is strongly suspected. Moreover, the association of one event with a major river flood raises the intriguing possibility that high bedload concentrations may be sufficient to generate sand suspensions, which continue downfjord along the bottom.

6) Bute Inlet offers a perfect natural laboratory in which to investigate the dynamics of active sand-transporting flows and elongated fan development. This depositional geometry is analogous to many ancient fans on active margins (*11*). The occurrence of similar channel depositional systems in neighboring fjords in British Columbia, such as Toba Inlet, provides opportunities for comparative studies.

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Accelerated Healing of Incisional Wounds in Rats Induced by Transforming Growth Factor–β

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The role of polypeptide growth factors in the processes of inflammation and repair was investigated by analyzing the influence of transforming growth factor–β (TGF-β), applied directly to linear incisions made through rat dorsal skin. A dose-dependent, direct stimulatory effect of a single application of TGF-β on the breaking strength of healing incisional wounds was demonstrated. An increase in maximum wound strength of 220 percent of control was observed at 5 days; the healing rate was accelerated by approximately 3 days for at least 14 days after production of the wound and application of TGF-β. These increases in wound strength were accompanied by an increased influx of mononuclear cells and fibroblasts and by marked increases in collagen deposition at the site of application of TGF-β. TGF-β is thus a potent pharmacologic agent that can accelerate wound healing in rats.

Growth factors present in serum and platelet extracts are considered to play important roles in inflammation and wound healing (*1–3*). The platelet-derived growth factor (PDGF) and platelet factor 4 at low concentrations were first shown to be chemotactically active for human monocytes, neutrophils, smooth muscle cells, and fibroblasts (*4, 5*) and to stimulate inflammatory cells and fibroblasts (*6*), activities which indicated that these proteins were important in inflammation and repair. Another polypeptide growth factor, transforming growth factor–β (TGF-β), originally identified in conditioned media from transformed cells (*7*), was subsequently found widely distributed in tissues (*8*) and in very high concentrations in platelets (*8, 9*). Evidence that TGF-β may be important in wound healing included stimulation of total protein, collagen, and DNA content in wound chambers implanted in vivo (*10*), stimulation of expression of fibronectin and collagen by fibroblast lines in tissue culture (*11*), and rapid, reversible formation of granulation tissue when injected subcutaneously into newborn mice (*12*). TGF-β also manifests growth-inhibitory properties for specific cell types (*13, 14*) and thus may serve as a bifunctional regulator of cellular growth and differentiation (*9*).

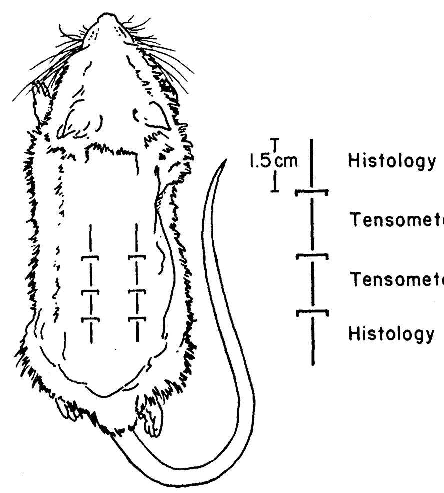

Fig. 1. Young adult male Sprague-Dawley rats, 300 to 350 g (Sasco; Omaha, Nebraska), anesthetized with pentobarbital, had 6-cm linear incisions placed through the skin 1.5 cm on either side of the midline. A bovine collagen suspension, an equal volume of saline, or nothing was applied to the sides of each incision, with each animal serving as its own control. The wounds were then coapted with three surgical clips. For study, the entire dorsal skin of the rat was excised. A template with parallel surgical blades was used to excise two 8-mm strips between clips from each incision. Histological samples were taken from the ends.

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