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Temporal progression and spatial extent of mass wasting events on the Squamish prodelta slope

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ABSTRACT: The cumulative mass wasting activity on the Squamish River prodelta slope has previously been monitored using repetitive multibeam surveying for a period of 6 years using biannual, annual or semi-annual intervals. The majority of the activity is clearly linked to the summer freshet conditions in the river and focused into three discrete channels. To address how frequently the individual events happen and to explore the likely mechanisms, a higher survey frequency has been implemented with 1 to 3 day survey intervals during the freshet. In all, 93 surveys were conducted, identifying 106 channel-specific mass wasting events and 30 turbidity currents. To qualitatively monitor the style of turbid intrusions from the delta front, volume scattering cross-sections were derived from multibeam water column imaging along each of the major channels. Intrusive, seabed-following, displacements of the deep scattering layer together with bottom-mounted ADCP events clearly indicate active turbidity currents.

1 INTRODUCTION

1.1 *Area of operations*

A dedicated 10 month experiment has been implemented on the Squamish Delta, flowing into Howe Sound, British Columbia. The delta has been estimated to receive more than one million cubic metres of sediment per year (Hickin 1989). Since 1971 all the discharge has been constrained by a training dike into a delta front that is only 500 m wide.

The area is macrotidal with spring tides up to 5 m in range and neap tides in the 3 m range. At low water springs, the full river discharge is constrained within a subtidal channel that is about 1 m deep and only 200 m wide at the lip of the delta. Seaward of the delta front, there are three main active channels (Fig. 1). The northern and central channels extend ~1km from the delta top lip. The southern channel extends an additional kilometre. Beyond these distances, the channel morphology disappears and the flows appear unconstrained and free to laterally spread. Within all the channels trains of crescentic bedforms (Paull et al., 2010) are well developed.

The cumulative change over the freshet period is illustrated in Fig. 2. In 2011 it is clear that there has been net regression of the delta lip. All three channels have been active. Both the southern and central channels were primarily flow-through conduits with deposition occurring on a proximal lobe seaward of the channel termination. A plug of sediment (arrow in Fig. 2) was introduced into the northern channel (almost all of it on JD181) filling the talweg and subsequently diverting the flow outside the channel.

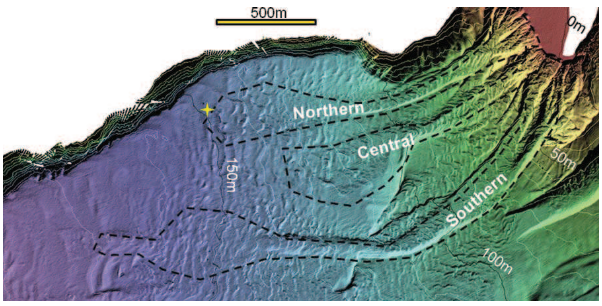

Figure 1. Bathymetry of the three active channels on the Squamish prodelta. The star marks the ADCP location.

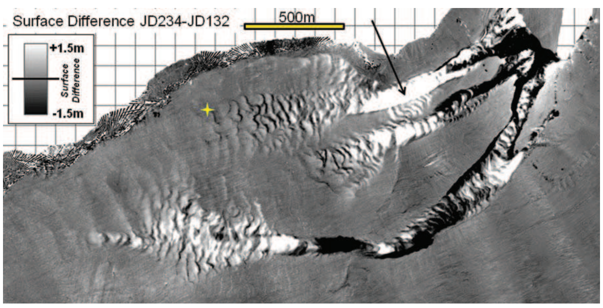

Figure 2. Cumulative bathymetric difference JD234-JD122 (May 2nd to August 22nd). Greyscale +/−1.5 m. Maximum deposition is 8 m and maximum erosion is 12 m. Arrow indicates sediment plug.

1.2 *Previous work*

The delta has been the focus of previous surveys including single beam hydrographic surveys in 1973 and 1990 and a sidescan survey in ~1980 (Prior & Bornhold 1984). From 2004 until 2009, 9 multibeam surveys of the prodelta have been conducted at intervals either of 2 years, one year or 6 months (Brucker et al., 2007, Hughes Clarke et al., 2009).

Based on the observed changes over biannual, annual and semiannual multibeam surveys, it is apparent that by far the majority of the prodelta morphological evolution takes place during the summer freshet. While the net change over this period is well described, the mechanisms and timing of individual sedimentation events is unknown.

Previous work looking at turbidity current activity in Bute and Knight Inlets using bottom mounted instrumentation (Prior et al., 1987, Bornhold et al., 1994) clearly illustrate that in such fjord environments many tens of events could be expected in a summer freshet period. At the time, there was no ability to precisely resurvey the upstream morphology to detect small-scale change to provide insight into the driving mechanisms.

1.3 *Rational for current investigation*

This study attempts to build on the previous observations of fjord turbidity current activity by combining seabed current observations with corresponding daily maps of the changing morphology upstream of the flow events as well as water column volume scattering images along the channels.

Given the advances in multibeam and ancillary sensor technology, it is now possible to monitor changes in seabed relief at these depths at a scale that can identify migration of short wavelength (<10 m) morphologic features (Hughes Clarke 2012). Notable pioneering work in this field has been undertaken by Hill (2012) on the Frazer Delta prodelta slope.

Using a dedicated survey platform, based in Squamish, it was possible to put on a 10 month program (Fig. 3) with daily surveys during the active summer freshet period. The aim of these frequent surveys was to capture the changes in morphology within periods as short as 24 hours so that small scale migration of bedforms (both on the delta top and within the channels), progradation of the delta lip, development of slump scars, and emplacement of debris flow-type events could be detected. The hope was that these events could be correlated with bottom mounted ADCP records at a distal location as well as acoustic water column imagery and optical backscatter profiles within the channels.

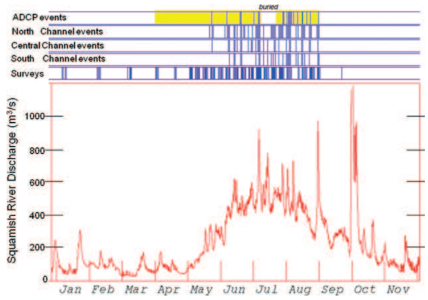

Figure 3. Timing of surveys and corresponding detected seafloor events. Graph illustrates 2011 discharge of the Squamish River (at Brackendale, Environment Canada station 08GA022). Shaded interval is the ADCP deployment window.

2 METHODOLOGY

2.1 *Multibeam bathymetric and backscatter operations*

All the 93 surveys conducted were undertaken from the CSL Heron which is a 10 m long survey launch, equipped with an EM710 multibeam sonar. The sonar has a 1° transmit beam width and a 2° receiver beam width. It operates using 3 sectors per swath generating two discrete swaths over a single transmission cycle. The sectors are assigned discrete frequency bandwidths in the range 70 to 100 kHz. The system is roll, pitch and yaw stabilized.

The EM710 provides bathymetric data with a typical horizontal spatial resolution of ~3% of depth with a vertical accuracy in the range of ~0.2% of depth. As well as bathymetric data, backscatter data collected within each beam forming channel can be combined to generate a map of the estimated seabed backscatter strength.

All the data were positioned using C-Nav RTG GPS solutions with a horizontal uncertainty at about the 30cm level (2 sigma). Preliminary vertical referencing (used for results herein) was done with predicted tides, although Point Atkinson tidal observations are now available. In addition, for all operations an Ellipsoid height solution will be available after PPP/PPK processing of GPS raw observables.

The survey program achieved the following survey extents and repeat periods during the freshet period:

- Active Prodelta (5 m to 200 m) surveyed on every weekday.
- Delta-Top Channel (0-5 m) surveyed twice per week to 1000 m upstream of lip.
- Distal Prodelta and ponded fjord basin (up to 16 km from the delta) on a two weekly interval.

The aim was to resolve changes in prodelta morphology on a daily basis (excepting weekends due to heavy recreational activity in the area). Each pair of surveys was differenced to try and detect bathymetric change. For the distal regions, the focus is on trying to detect subtle changes in backscatter character to infer surficial sediment changes as the bathymetric change would be beyond the achievable resolution (<20 cm in >200 m of water).

2.2 *Water column imaging*

As well as seabed topography and backscatter, the EM710 is capable of logging the received acoustic volume scattering from the water column along each beam's path prior to arrival at the seabed. At a slant range greater than the minimum distance to the seafloor, the volume scattering is contaminated by seafloor side lobe interference (Hughes Clarke, 2006). Thus the unambiguous water column imaging is restricted to a ~half cylinder under the vessel track. Within this region, water column scatterers including zooplankton, and gas plumes can clearly be seen. In addition any interfering sonars or propeller noise can be detected.

Most notably Howe Sound is strongly stratified in zooplankton. During the day time, when the acoustic imaging was taking place, the zooplankton (probably euphausids and copepods by analogy with other better studied nearby fjords, (Greenlaw 1979) migrate to the lower section of the fjord.

As became apparent during the survey, any intrusions of sediment-laden water from the delta front, would actively displace the zooplankton-laden water masses resulting in an anomalous region of low scattering strength. Thus the presence and volume distribution of intrusions can be qualitatively monitored.

The example in Figure 4 illustrates typical volume scattering anomalies in the presence of an intrusion. The basal intrusions are characterized by a bottom following anomaly. On several days however, parts of that intrusion would break away from the main flow and follow a iso-density horizon indicating that the flow did not have enough excess density to continue descending.

To investigate the recent passage of a turbidity current-like event, on a daily basis three longitudinal sections were derived along the axis of the three major distributary channels. In addition, after JD 174 an optical backscatter probe was lower to a depth of 125 m (maximum cable length) within each channel on a daily basis to try and detect suspended sediment anomalies. Examples of the results are illustrated in Figure 5. A slightly elevated near seabed optical backscatter signature (< = 0.01 g/l) was present on most days. Whenever intrusions were suggested from acoustic imaging however, additional anomalies were associated with these events.

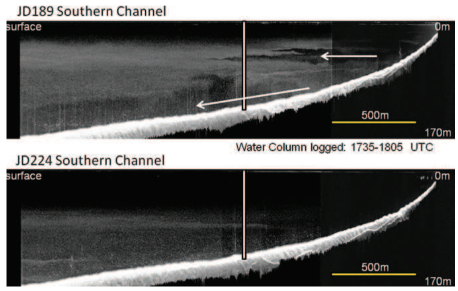

Figure 4. Example multibeam water column sections along the axis of the southern channel. Lower example shows a typical section when no intrusions were taking place. The upper figure shows an example of when both a seabed-following intrusion and a mid-water intrusion was taking place.

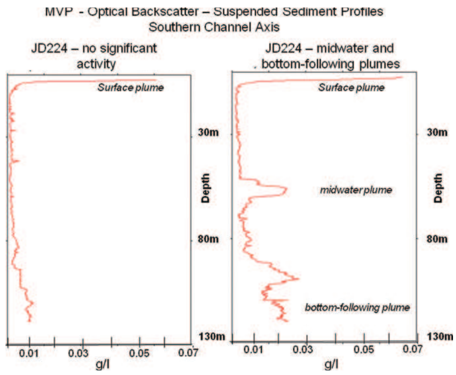

Figure 5. Optical backscatter profiles within the southern channel at the days and locations indicated in Figure 4. The data are presented as g/l units but should be considered preliminary as they are based on the calibration of a different, but identical model sensor.

2.3 *ADCP observations*

A 600 kHz RDI Sentinel ADCP was deployed at a depth of 150 m in the path of the northernmost channel (Fig. 1, star). The ADCP was set to collect 17 ping ensemble averages every 30 seconds. The ADCP battery life was ~1 month, but the instrument was typically recovered every 2 weeks to try and minimize the effects of rapid burial and entanglement in branches and tree limbs that were subsequently found to be moving across the seabed.

The system recorded data in 50cm thick bins. The instrument was mounted ~50cm above the seabed (before burial) and the centre of the first bin was 1.6 m above that. Thus the lowest current and 600 kHz acoustic volume scattering signal was observed 2.1 m above the seabed. There were 90 bins and thus the highest possible observation was 47 m above the seabed.

The instrument was first deployed on the 29th March 2011 (JD088) and finally recovered on the 23rd August 2011 (JD235). It recorded almost continuously over that period with the exception of a 20 day period from 30th June to 20th July (JD181-201) when it was apparently buried. This burial corresponded directly to the major event that completely filled and subsequently diverted flow in the lower section of the northern channel (Fig. 2).

The location of the instrument was deliberately chosen to be immediately downstream of the path of the northern channel. While the southern channel had previously been noted to be the most active, a surface mounted buoy was not possible there due to active shipping traffic. The location in the distal part of the northern channel was chosen to be just beyond the region in which significant (>1 m) change had been previously observed. This was in the hope that flows would not be so erosive or depositional that they might exhume or bury the instrument.

A result of this location is that events in the central channel may not actually impact the instrument and events in the southern channel would definitely not affect it. Thus it is predominantly a record of events in the northern channel only.

3 MASS WASTING ACTIVITY DETECTED

3.1 *Mass wasting activity*

Over the 82 day period when surveys were performed 5 days per week, a total of 106 channel-specific mass wasting events were detected through inter-survey change analysis. During that period (with one 20 day interruption), 30 distinct turbidity current events were detected from the bottom mounted ADCP.

3.2 *Inter-survey bathymetric differences*

From day to day the terrain model was subtracted from the previous survey to look for patterns of seabed change. At the very limit of detection (~20–30cm change over wavelengths of >5 m), there is superimposed noise related to systematic biases in the multibeam data including: integration biases (alignments and offsets), refraction residuals, horizontal positioning limitations (the real time data using RTG had correction disruptions where the horizontal positioning error could be as much as 2 m). The manifestation of such errors, however, are usually clearly related to the imaging geometry, generating residuals that follow, or are orthogonal to, the survey tracks. Where possible, alternately orthogonal survey line orientation was chosen to highlight and isolate non-morphologic error sources.

Between a given pair of surveys, the signature of individual channel events could easily be discerned. Figure 6 illustrates a typical example when two of the three channels were active. Typically (but not always), the upslope end of the disturbances would be associated with a pronounced excavation of sediment near the delta lip. Downstream, the crescentic bedforms in the channels would invariably be displaced upslope. For the majority of events, the displacements would terminate before, or at the end of the channelized sections. For a small subset of the events, the displacements would continue out and spread radially over the lobate unchanneled distal region.

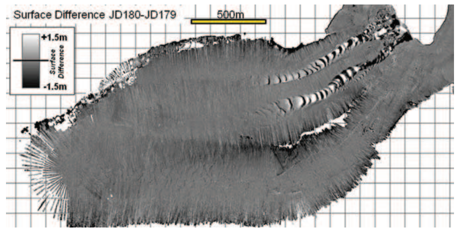

Figure 6. Example 24 hour seabed change map. The area covered is identical to Figures 1 and 2. The water column imaging associated with the second survey is presented in Figure 7.

3.3 *Water column imaging*

On every weekday, three critical transects were run along the Northern, Central and Southern Channels and later on a standard transect across all three at the 100 m contour. The typical duration of the channel lines was about half an hour. During that period, the water column imaging provides a snapshot of any displacements of the deep scattering layer that might indicate an intrusion of water.

Figure 7 illustrates simultaneous active intrusions along the two channels that were active on JD180 (when the bathymetric difference map in Fig. 6 was derived). Four features are evident:

1. at the surface the ebb-tide river plume shows up clearly within the top 5 m.
2. a diffuse cloud of scattering is associated with the sub plume region immediately seaward of the delta lip. This is inferred to be a signature of sediment settling out of the plume.
3. deeper than ~50 m (the upper limit of the daytime zooplankton layer) the deep scattering layer appears to be pushed aside by a flow that is descending, following the bottom.
4. a subset of that descending plume appears to break away at about 75 m depth and travel out horizontally, presumably following an iso-density horizon.

While the acoustic water column imaging allows a determination of the sectional and volumetric extent of these intrusions, no quantitative measure of their content can be derived. To address that, static optical backscatter (and CTD) profiles

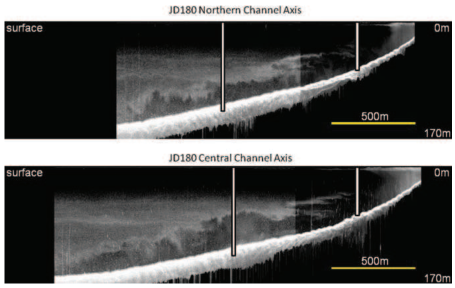

Figure 7. Multibeam water column vertical sections along the talweg of the Northern and Central channels on JD180, corresponding to the difference map in Figure 6. The vertical lines indicate the position of optical backscatter profiles shown in Figure 8.

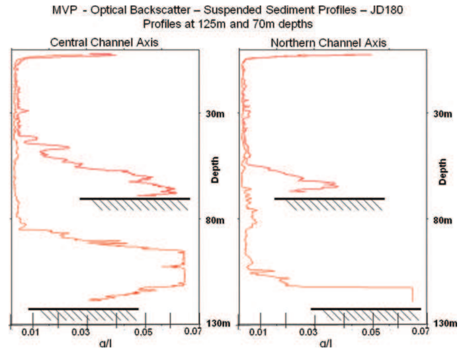

Figure 8. Optical backscatter profiles from the 4 locations indicated in Figure 7.

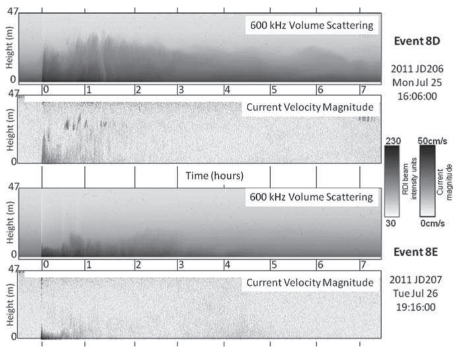

Figure 9. Eight hour time series of ADCP data (600 kHz acoustic volume scattering and current magnitude) for two discrete turbidity current events detected.

were obtained at one or two locations in each channel.

Figure 8 illustrates the results from the sections shown in Figure 7. All profiles indicate the high suspended load in the river plume in the upper 5 m. As can be seen, in the channel floor at 70 m depth, there is a well developed increase in suspended sediment as the channel floor is approached. At 125 m depth the suspended sediment concentration peaks even higher. For several events (including this example), the optical backscatter probe went off scale indicating sediment concentrations in excess of ~0.07 grams per litre. In this example, in the central channel, the peak suspended sediment concentration appears suspended above the bottom, possibly indicating that the flow density is close to the ambient seawater density at this depth.

For some, but not all of the highest recorded suspended sediment events, a faint drop in salinity was also associated with the peak load. The majority of events however, showed no significant salinity or thermal anomaly over the surrounding seawater.

3.4 *ADCP results*

The ADCP installation recorded 30 discrete turbidity current events over the time period.

For the first 49 days, no turbidity currents were recorded. On that day (17th May, JD137), the first and largest event of the year was recorded (1.5 m/s maximum current velocity). Within the subsequent 44 day period prior to burial, 7 turbidity current events were observed.

After exhumation, the ADCP logged data for a further 34 days during which 23 more turbidity current events were detected.

A typical event (e.g., Fig. 9) showed an abrupt front, with a near-basal peak velocity of ~50cm/s. The duration of the main flow event was typically about one hour. A suspended sediment plume was inferred from the 600 kHz volume scattering recorded within each ADCP cell (Fig. 9). Although the absolute suspended sediment levels cannot be derived, the relative intensity can be used to infer the change in suspended load and the height and duration of the discernable suspended sediment plume. Flow thickness was quite variable with a range from ~10 m to 40 m. Plume duration was normally in excess of 7 hours. Suspended sediment load appears to decline from peak levels at the base of the flow. Often the head of the flow was dense enough to actually block the acoustic profiler from making useful measurements above ~10 m.

3.5 *Inter-correlation of survey change events with water column and ADCP record*

The inter survey bathymetric differences represent the net seabed change over either a 24 hour or a 72 hour period. As the current events detected by the ADCP indicate, the period of high velocity flow was generally no more than two hours. The turbid cloud, however, that remains after the passage of the turbidity current is notable for over 7 hours.

The water column imaging provides a snapshot of displacements of the deep scattering layer that are present within a ~45 minute period.

Thus correlating the three types of observations is tricky. The event(s) that cause the bathymetric change need not be associated with the event currently perturbing the deep scattering layer. Nevertheless, no intrusive events were ever detected without associated seabed change.

Only a subset of the northern channel bathymetric change events are associated with an ADCP event (Fig. 3). Presumably, the majority of the events decayed before reaching the ADCP location.

4 INTERPRETATION

Daily bathymetric difference maps indicate that the net morphological evolution of the prodelta slope over the summer freshet period is the result of multiple successive short-lived mass wasting events. The majority can be traced to a discrete collapse of the lip of the delta front. Resulting turbidity currents are short-lived surge events rather than indicative of a sustained hyperpycnal flow. The lack of a reduced saline signal in the remnant turbidity suggests resuspension through mass wasting rather than direct injection of high density fluvial discharge.

The floors of the channels exhibit arcuate cyclic transverse features with an asymmetric steplike morphology. These have the steeper face, facing downslope. Proximally, these transverse features appear to resemble rotational slump morphology. Distally however, the relief is more subdued and the asymmetry disappears suggesting a more antidune-like resemblance.

In every case, whether or not a slump scar is seen at the head, a chain of displacements of these transverse features is seen along the channel axis. The net result of every event (in which the before and after transverse features are still correlatable) clearly indicate an upslope migration of these features.

Upslope migration is understandable for an antidune like origin, suggesting supercritical flow. The arcuate, convex upslope morphology could be explained by higher migration rates in the centre of the channels. The rotational slump scar model (Paull et al., 2010) is harder to associate with the upslope migration in this case.

5 CONCLUSIONS

Preliminary results indicate a clear correlation between seabed morphologic change, mid water and seabed-following water column intrusions and ADCP current events. This indicates a genetic link between the mass wasting and turbid intrusion events on the Squamish prodelta slope.

The upslope migration of crescentic bedforms starting almost immediately downslope of the source mass-wasting event suggests a rapid transition into a turbid suspension. Details of this transition remain enigmatic, however, as the locale is particularly hard to instrument.

ACKNOWLEDGEMENTS

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REFERENCES

Bornhold, B.D., Ren, P. & Prior, D.B. 1994. High-frequency turbidity currents in British Columbia fjords. *GeoMar. Lett.* 14: 238–243.

Brucker, S., Hughes Clarke, J.E., Beaudoin, J., Lessels, C., Czotter, K., Loschiavo, R., Iwanowska, K. & Hill, P. 2007. Monitoring flood-related change in bathymetry and sediment distribution over the Squamish Delta, Howe Sound, British Columbia. In *U.S. Hydro. Conf. 2007*, p. 16.

Greenlaw, C.F. 1979. Acoustical estimation of zooplankton populations. *Limnol. Oceanogr*. 24(2): 226–242.

Hill, P. 2012. Changes in submarine channel morphology and slope sedimentation patterns from repeat multibeam surveys in the Fraser River delta, western Canada, *IAS Special Publication* #44., Part 1.

Hickin, E.J. 1989. Contemporary Squamish River sediment flux to Howe Sound, British Columbia. *Canadian Journal of Earth Sciences* 26: 1953–1963.

Hughes Clarke, J.E. 2006. Applications of multibeam water column imaging for hydrographic survey. *The Hydrographic Journal* 120: 3–15.

Hughes Clarke, J.E. 2012. Optimal use of multibeam technology in the study of shelf morphodynamics. In *IAS Special Publication* #44., Part 1.

Hughes Clarke, J.E., Brucker, S., Hill, P. & Conway, K. 2009. Monitoring morphological evolution of fjord deltas in temperate and Arctic regions. In International Conference on Seafloor mapping for Geohazard Assessment, Editors: Chiocci F.L., Ridente D., Casalbore D., Bosman A, *Società Geologica Italiana*, Vol. 7, part 4, pp. 147–150.

Paull, C.K., Ussler. W., Caress, D.W., Lundsten, E., Covault, J.A., Maier, K.L., Xu, J. & Augenstein, S. 2010. Origins of large crescent-shaped bedforms within the axial channel of Monterey Canyon, offshore California. *Geosphere* 6(6): 755–774.

Prior, D.B. & Bornhold, B.D. 1984. Geomorphology of Slope Instability Features, Bathymetry Squamish Harbour, Howe Sound, British Columbia. *Geological Survey of Canada, Open File* 1095.–2 Maps. 1-10,000.

Prior, D.B., Bornhold, B.D., Wiseman, W.J. & Lowe, D.R. 1987. Turbidity current activity in a British Columbia fjord. *Science* 237: 1330–1333.