Monitoring morphological evolution of fjord deltas in temperate and Arctic regions

John E. Hughes Clarke, University of New Brunswick, CANADA, jhc@omg.unb.ca
Steve Brucker, University of New Brunswick, CANADA, steveb@omg.unb.ca
Philip Hill, Geological Survey of Canada, CANADA, Philip.Hill@NRCan-RNCan.gc.ca
Kim Conway, Geological Survey of Canada, CANADA, Kim.Conway@NRCan-RNCan.gc.ca

Repeat multibeam surveys of the prodelta slope of fjord deltas are used to monitor and compare the temporal evolution of the surficial morphology.
Six multibeam surveys of the temperate Squamish River Delta, over a period of 4 years, illustrate the cyclic evolution of the feeder gullies, axial channels, and distributary lobes. The temporal evolution clearly indicates that slope–transverse undulations are upslope-migrating bedforms, rather than slope creep phenomena.
A second monitoring program has been initiated using the same methods but in the fjords of Baffin Island. Maintaining the same survey accuracy at high latitudes is much more difficult due to low satellite geometries and lack of precise vertical control.

Introduction. Fjord deltas usually represent sites of enhanced sedimentation and mass wasting. The main depocentres usually lie within a few kilometres of the river mouth at depths of 100-200 m, and are therefore readily accessible by surface-mounted multibeam sonars. The time scales of morphological evolution are short, with measurable annual change. As such, they represent useful small-scale analogs for much less frequent, deeper-water mass wasting environments. The physical processes active on a fjord delta reflect both the volume and type of input sediment, as well as the exposure of the delta front to tidal, wave and potential iceberg activity.

Two parallel programs have been undertaken using multibeam bathymetry and backscatter in order to map, monitor and contrast the temporal and spatial evolution of active fjord deltas in both temperate and Arctic regions. Six surveys of the front of the Squamish delta in Howe Sound, British Columbia (*Prior and Bornhold, 1984*) have been completed over four years *(Brucker et al., 2007).* In the Canadian Arctic, repeat multibeam surveys of three deltas in Oliver Sound (Baffin Island), spaced two years apart, have been completed. Additionally, the first surveys of four other deltas on northern Baffin Island have been implemented for future resurvey.

The Surveying Challenge: In order to meet the research objective of monitoring annual morphological change on prodelta slopes, the typical scale of spatial change must be greater than the total integrated accuracy. For both temperate and Arctic deltas, inter-annual change occurs over scales as small as 0.5 m vertically, and 10 m horizontally. This change involves regional accretion and deflation, bedform migration, and mass wasting phenomena.

The resolution of the multibeam sonar is dependent on hardware, depth and geometry. Translating this resolution into absolute accuracy requires integration of the sonar-relative solutions with commensurate accuracy in position, orientation and sound speed field. Particularly in Arctic regions, achieving the necessary level of precise integration is a logistical challenge, which limits the absolute ability to monitor seabed change.

Methods. Surveys of the Squamish River Delta have been performed using both EM1002 and EM3002S multibeam sonars. The Arctic deltas were all surveyed using an EM3002S. Actively changing morphology was noted at depths up to 200m. At these depths, the required spatial resolution of < 10m can easily be met with the beam widths of the sonar utilized (1.5 to 2°). Therefore the total achievable accuracy is primarily limited by the aiding sensor accuracy and integration issues rather than the sonar resolution itself.

For both regions, wide-area satellite-based GPS services (CDGPS for Squamish and CNav for the Arctic) were utilized, which would normally provide <1m horizontal positioning confidence. However, in both cases the extreme masking of the surrounding fjord topography and, for the case of the Arctic latitudes, low satellite elevations, would intermittently degrade the positioning accuracy. Gross positioning offsets were rare, and, when present, easy to edit out. More often, the poor satellite geometries caused slowly changing horizontal errors on the 5-10m scale that only become apparent during the seabed change analysis. This had little effect on the apparent depth in low slope regions, but in the steeper-sloped areas, the horizontal positioning errors generated significant apparent vertical offsets.

For the Squamish region, excellent tidal control is provided by both a permanent gauge at the mouth of the Sound and a temporary gauge, established in the local vicinity. For the Arctic regions, there are no permanent tide gauges, and constituent measurements from historic gauges are often unreliable. Logistical challenges provide no opportunity to establish a temporary gauge.
In order to better manage vessel squat and long-period heave drifting, PPK GPS was employed for some of the Squamish surveys and one of the Arctic surveys. More frequent use of PPK technology in the Arctic was often precluded due to low cloud restricting helicopter access to shore.
In order to provide a proxy for traditional tidal measurements in the Arctic, a hydrodynamic tidal model was developed for the Eclipse Sound region (*Church et al., 2007*) to predict the propagation of the tidal wave through the narrow inlets. The model can thus provide tidal solutions at multiple survey sites within the domain. In addition, post-processed GPS using precise ephemeris information (PPP) is being examined as a possible alternate means of vertical positioning.

As the deltas were examined during active river discharge periods, sound speed variability can induce systematic biases in the data, degrading the change analysis. For all EM3002 surveys, densely-spaced sound speed profiles were collected using an MVP-30 underway sampler. For the EM1002 surveys though, which were only part of larger regional mapping programs, the collection of sound speed information was insufficient.

Because of the large and rapidly fluctuating slopes in fjord deltas, it is necessary to post-process backscatter data to separate the topographic from the textural signatures. Otherwise, slope- driven backscatter fluctuations, especially over short wavelength relief such as the observed bedform fields, could easily be confused with sediment variability. Since the observed depth range approaches the extinction depth of the sonars, particular attention needs to be paid to proper choice of attenuation coefficients.

Results and Discussion. The most comprehensive results so far have been obtained from the temperate fjord delta where gross evolution over a 24 year period (using 1973 and 1990 single beam surveys) and detailed evolution over a 4 year period is available.

Figure 1 presents a synthesis of two years of evolution of the active section of the Squamish prodelta. As can be seen, the most change occurs over the summer period during which the snow-melt river discharge peaks. In the summer of 2006, a 600,000 m^3 section of the edge of the delta was removed, most of which was redeposited within the main channel axis. This resulted in a maximum of 26 m of erosion at the edge of the delta platform and 10 m of deposition in the main channel.
Over the following winter, change was minimal, with the notable exception of slowly migrating bedforms in a secondary channel. Because the bedforms in this channel have moved less than half a wavelength over the 6 month period, it is possible to clearly establish that they migrate up-channel. Over the summer months, because the bedforms migrate more than half a wavelength, it is hard to associate any particular crest with another crest 6

months later, and thus migration direction is ambiguous. Nevertheless, the morphology of the active bedforms during winter and summer is identical, and thus they are all inferred to be migrating upslope (and therefore up-current).
The following summer the reverse happened in the main channel. The scar in the upper reaches of the channel, left by the massive removal the previous summer, acted as a reservoir accumulating a comparable volume of sediment with a peak of 24 m of accretion. Downstream, it is clear that the bedforms along the axis of the channel have been very active, but there is no longer significant net accretion. The transverse patterns of erosion (up to 7m) and deposition indicate migration of the bedforms (direction cannot be discerned for the reasons stated earlier).
Thus a cycle is apparent between the two summers. In the first year, the pre-existing reservoir of sandy silt in the upper channel is discharged, and the second summer the same reservoir is recharged, blocking (but not stopping) flux further down the prodelta.

On the proximal depositional lobe immediately downstream of the axial channel, net accretion occurred over the summer of 2006 (when the discharge occurred), but not in the summer of 2007. For both summers, however, it is clear, that active migration of bedforms on the proximal lobe is taking place. In the summer of 2007, the displacement of the bedforms results in both accretion and erosion into the pre-existing surface. In the summer of 2006, in the locus of deposition, the trough locations do exhibit net accretion, but on the flanks of the depocentre, the bedforms displacement is continuing to erode into the pre-existing surface.
Downstream of the area illustrated in Figure 1, the EM1002 surveys in 2004 and 2005 show morphological evidence for downslope sediment transport extending onward for more than 10 km. This indicates that significant sediment is bypassing the proximal lobe. The fact that the migrating bedforms on the proximal lobe are partially eroding suggests that the more distal sedimentation may be derived from resuspension of proximal lobe sediments, rather than directly from discharge of the upstream reservoir.

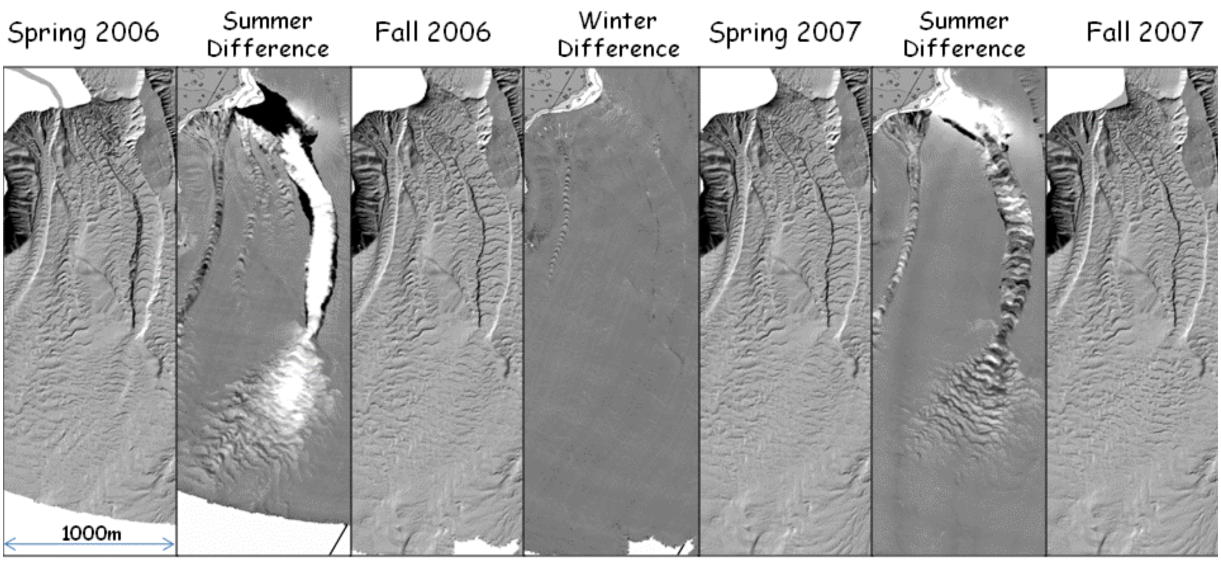

Figure 1. Evolution of the Squamish Delta over two years. Four EM3002 surveys, presented as sun-illuminated terrain models, extending from the 2m contour (delta top) to ~ 170m depth. For each pair of surveys, the surface difference is presented a greyscale (white >=3m accretion, black >= 3m of erosion).

Notably, the temperate delta has a singular and more strongly developed channel than the Arctic deltas. *Hill (2009)* has inferred that the well-developed and dominant axial channel, seaward of the main Fraser River mouth delta, may have been the result of artificial river stabilization on the delta top. The Squamish River discharge has similarly been focused through a training dyke installed in 1971. In both cases, the presence of a man-made barrier restricts the ability to naturally avulse. This contrasts strongly with the Arctic delta slope morphologies wherein multiple channels are apparent. Thin drapes, evident in subbottom profiling and the backscatter maps, indicate that only one or two channels are currently active. The inactive channels, however, maintain the surface morphological appearance of the active ones, suggesting that they have been abandoned only recently. Aerial photography of the delta tops indicates multiple sediment pathways to the delta front and, of course, no anthropogenic barriers to avulsion.

The Arctic deltas that have now been resurveyed, show a comparable level of activity to the Squamish delta. Those fed with fine-grained material (silty sand and finer), exhibit the same transverse bedforms as the Squamish. As with the Squamish, bedforms on the proximal lobes also exhibit migration wherein troughs clearly erode into pre-existing sediments. Uniquely, iceberg impact marks overprint the Arctic deltas as shallow smooth depressions. The extent of iceberg impacts appears to reflect both the local availability of icebergs and the rate of sedimentation. However, no evidence indicating mass wasting triggered by iceberg impacts has yet been obtained.

Conclusions. Sequential multibeam surveying of fjord deltas is an effective tool to delineate the spatial and temporal evolution of the surficial morphology. In this manner, the active processes can be measured rather than just inferred. Our detailed understanding of the processes, however, is ultimately limited by component survey sensor accuracies and the integration of the survey system used.

The near-ubiquitous slope-transverse periodic relief on the Squamish Delta is shown to be upstream-migrating bedforms, rather than rotational slumping or creep. This would suggest that turbidity currents, rather than debris flows, are the main mechanism for sediment transport along the channels and across the proximal lobe. The uppermost section of the main channel system is acting as a reservoir for fluvial deposition immediately seaward of the delta front. Such a phenomenon has been previously observed by *Hill (2009)* on the Fraser Delta. The reservoir appears to be periodically flushed out, which suggests that a significant fraction of the turbidity currents that mould the prodelta slope are generated from resuspension of reservoir accumulations, rather than directly from hyperpycnal flow as implied by *Mitchell (2005)*. There is, however, comparatively smaller volume transport during the winter months in other lesser channel systems, suggesting a secondary, but more continuous, mechanism for generating turbidity currents. Thus, significant hyperpycnal flow cannot be ruled out without direct long term current observations.

The predominance of a single major channel seen on the Squamish Delta, and the resulting tendency to have a single large reservoir, may be a function of the constraints placed on the delta by anthropogenic stabilization. The contrasting morphology seen on untampered Arctic deltas may be more representative of processes in the ancient record. The higher density of channels and apparent frequency of avulsing may preclude build up of large unstable sediment bodies. As most deltas in built up areas have been stabilized, this may pose a geohazard risk.

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