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Report to Prince William Sound Regional Citizens' Advisory Council:
Future Iceberg Discharge from Columbia Glacier, Alaska

Reference PWSRCAC Project #8551
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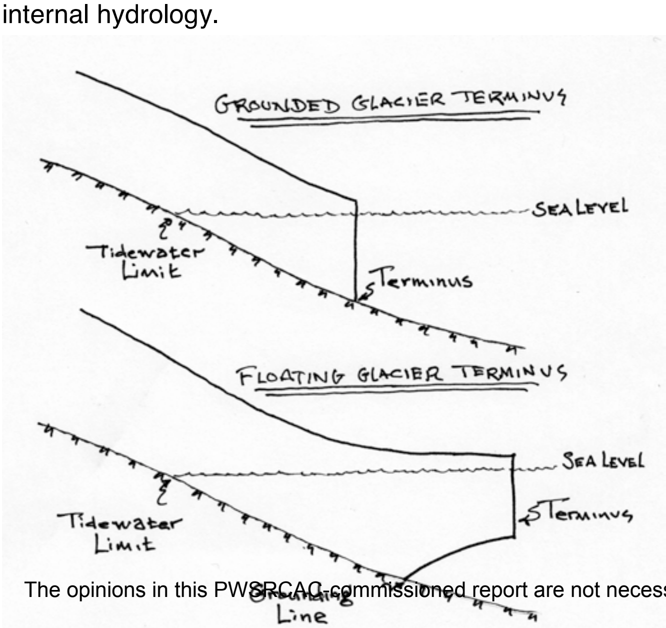
Report #4

1. Objective

Based on new analysis, evaluate and report on whether ice in the East Branch could be evacuated rapidly and whether any changes to the estimates established in previous reports will be necessary.

2. Introduction

Tidewater Limit *vs.* Grounding Line. The location where the bed of an ocean-ending glacier rises above sea level is referred to as the "tidewater limit." The location where the bed of a *floating* ocean-ending glacier comes in contact with the ocean floor is referred to as the grounding line. These terms are often used interchangeably despite referring to quite different things. We use the terminology *tidewater limit* here. It is the point at which the retreating terminus of a grounded ocean-ending glacier will lose contact with the ocean. It is also the upstream limit of direct influence of the ocean on the glacier's mechanics and hydrology when the glacier is extended past the tidewater limit, although the terminus region can then still communicate with the glacier above the tidewater limit through the glacier's internal hydrology.



Several new pieces of information concerning Columbia Glacier's subglacial topography came to our knowledge around the time of the release of Report #3 and subsequently. These include the Rignot et al (2013) WISE airborne radar soundings noted in Report #3, seismic surveys of marine sediments near and downstream of the present terminus, and the continued calving retreat of the glacier's West Branch well past the location previously believed to the tidewater limit.

These three factors lead us to believe that the basal topography calculated by McNabb et al (2012) underestimates the depth of true bed throughout, and that the glacier's East Branch in particular (see Figure 1) is substantially deeper than previously indicated. This would result in more ice being stored in the East Branch basin, and provide a source for rapid release of icebergs under the right circumstances. The relevant information is fairly fragmentary, so the revisions presented here are necessarily rather approximate. A more complete airborne radar survey, coordinated with us, would give us the necessary information, but to our knowledge the operators of the WISE airborne radar have no further plans to fly in Alaska. In the analysis that follows we attempt, as we have done previously, to construct two or more outcomes that bracket the likely actual event.

3. New Information

Knowledge of a tidewater glacier's subglacial topography is fundamental to predictions of the glacier's future behavior, but it is also the most difficult geometric parameter to observe directly. Basal topography in the distal portion of the glacier resting on bedrock below sea level is particularly important for predicting rapid calving and retreat, just as has occurred at Columbia Glacier from the early 1980s to the present. At the time of our earlier reports, our best knowledge of the glacier bed still occupied by ice was the McNabb et al. (2012) 100 m-resolution full glacier bed, modeled from velocity data (Figure 1). But three new findings have cast doubt on the validity of the McNabb bed, and suggests that our earlier projected timing and magnitude of ice discharge require some revision. The most significant changes appear to be in the glacier's East Branch, and our revisions are limited to this region. Of the three new data sources described below, two (West Branch retreat and Post-retreat sedimentary infill) provide evidence that the McNabb bed is flawed, while the third (Airborne Radar Soundings in East Branch) gives new (but incomplete) observational constraints on the bed depth in the East Branch.

a. **West Branch Retreat:** Columbia Glacier's West Branch has always been assumed to be grounded above sea level immediately upstream from the West/Main Branch confluence and therefore not subject to the dynamic instability responsible for the rapid retreat in the Main Branch channel. Following the separation of the West and Main Branches in 2009, the stability of the West Branch terminus was consistent with this assessment. However, over the past year the West Branch terminus abruptly retreated 2.5 - 3 km, well beyond the previously assigned location of the tidewater limit, demonstrating that the bed here is substantially deeper than the McNabb model results suggest (Figure 2).

b. **Post-retreat Sedimentary Infill:** Recent seismic surveys by Boldt et al. (in prep) have found $3.2 \pm 0.6 \times 10^8$ m^3 of fine-grained sediment in the glacier forebay, from 50 to 100 m thick in places (Figure 3). The post-retreat bathymetry in the forebay seaward of the retreating terminus is this shallower than the bathymetry when the forebay was occupied by ice. Subglacial topography inferred from velocity/continuity calculations, as done by McNabb et al (2012), O'Neel et al (2005), and others, used the post-retreat bathymetry as an initial condition, and their calculated subglacial topography is accordingly biased, probably toward shallower depths. Again, this consideration suggests that the McNabb bed, throughout the glacier but on the East Branch in particular, is anomalously shallow.

c. **Airborne Radar Soundings in East Branch**: Newly released radar soundings by Rignot et al. (2013) from the Warm Ice Sounding Explorer (WISE) suggest an average 100 m deeper bed overall, and a previously undetected overdeepening in the fjord up the East Branch. This new data indicated the presence of ice up to 900 m thick lying in 250 m deep water in the East Branch. Given the evidence if the West Branch retreat and the forebay sedimentation, we are inclined to accept Rignot's depths over the McNabb calculated bed at this point.

Since the Rignot radar traces are sparse and located in less-than-optimal locations, we cannot say with confidence what the East Branch subglacial topography is, but we can use the Rignot data as a constraint to estimate both the increased ice volume in the East Branch and to get a rough idea of the potential dynamic instability arising from the bed topography between the present terminus and the revised (Rignot) East Branch tidewater limit. We summarize these estimates in the next section.

4. Preliminary Analysis

In addition to differing depths, the McNabb bed and Rignot profiles conflict in shape as well, and no comprise geometry can be found that satisfies both sources. Nevertheless, we can make a rough estimate of the East Branch ice volume consistent with a channel with the general shape of McNabb's bed but the depth of the Rignot profiles. Using this compromise, we estimate the East Branch ice volume between the Rignot tidewater limit. This volume, using the deeper Rignot bed, is roughly 33 km^3. The volume of ice between the McNabb bed and the Rignot bed as is roughly 15 km^3. The deeper Rignot profile thus entails approximately 15 km^3 more ice than the McNabb bed. At recently observed flux rates of ~ 2 $km^3\ yr^{-1}$, this *additional* ice would be evacuated in ca. 7 to 8 years.

There are two issues to be resolved in predicting the consequences of the deeper East Branch bed. The first of these is the additional ice volume in the East Brach, and in the absence of better and more complete radar bathymetry, the estimates above (33 km3 total) can't be improved upon much. The other issue is the increased likelihood of rapid dynamic discharge from the deeper East Basin. Useful predictions of this aspect require 1) an estimate to the time that rapid discharge will commence, 2) an estimate of the ice volume remaining at that time that is vulnerable to rapid evacuation, and 3) an estimate of ice flux during rapid evacuation. Again, without more complete knowledge of the subglacial topography, these questions can't be precisely addressed, but some simple estimates are possible.

4.1) Time to onset of rapid discharge. Using the instability criterion of Pfeffer (2007), rapid retreat is only possible in those reaches of the East Branch grounded below sea level (show in Figure 6 as regions 1 and 2), and the onset of rapid retreat starts if the ice thickness declines to a certain fraction of the water depth. (The critical ratio, given by model parameters discussed in Pfeffer (2007), is $H_{ice}/H_{water} \approx 1.85$.) This critical thickness is shown as a dashed blue line in both regions 1 and 2. For region 1, the ice surface height must fall ca. 120 m to 89 m above sea level; for region 2, the surface ice height must fall ca. 500 m to 150 m above sea level. At nominal thinning rates of ca. 20 m yr^{-1}, the time to the critical thickness would be ca. 6 years for region 1 and 25 years for region 2. The future thinning rate in the East Branch is highly uncertain, but on this simple basis, it is reasonable to expect that rapid retreat in these regions could start in ca. 5 years and persist for ca. 15-20 years. Note, however, that rapid retreat will be terminated when regions 1 and 2 are exhausted of ice, which may tale less than 20 years. We will see below that this is likely the case.

4.2) Estimate of ice vulnerable to rapid evacuation. Using the mean ice thickness of regions 1 and 2 at H_{crit} of ~ 250 m, the combined length of the regions of 1.75 km (here the entire span from the downstream edge of region 1 to the upstream edge of region 2), and an estimate of the glacier width at that time of 1 km, the resulting volume is the product of these dimensions, or 0.44 km^3. Note that this is a small fraction of the total ice volume in the East Branch.

4.3) Ice flux during evacuation. Many variables come into play here, and a robust calculation is out of reach, again, without better geometric information; even then, most assessments will rely on comparisons to previous stages of Columbia's retreat. Here, typical ice velocity during other stages of rapid retreat is used to calculate the lifetime of the 0.44 km^3 of ice estimated above, and alternatively, the lifetime is allowed to vary and the corresponding ice flux is calculated.

4.3a. Assume terminus flow speed is 10 m d^{-1}. This is a typical speed for modest rapid retreat seen elsewhere on Columbia Glacier. At the reduced size for rapid retreat, ice would pass through a cross-sectional area of roughly (1 km wide x 250 m thick) = 0.25 km^2, resulting in an ice flux of 0.0025 km^3 d^{-1}. At this flux, the 0.44 km^3 reservoir would be exhausted in ca. 180 days.

4.3b. Vary lifetime of rapid retreat as a parameter. If the duration of rapid retreat varies, the ice flux will vary inversely with it. Using the vulnerable volume of 0.44 km^3 as a fixed parameter, the ice flux is calculated for several choices of lifetime of rapid evacuation, and shown in this table:

Ice flux during rapid evacuation for given lifetime. Ice reservoir fixed at 0.44 km^3.				
Lifetime of rapid evacuation (y)	0.25	.05	1	2
Ice Flux (km^3 $year^{-1}$)	1.76	0.88	0.44	0.22

5. Summary. Without a more completely and carefully planned aerial radar survey a more robust and quantitative analysis of the effects of the added ice volume and greater ice depths is not feasible. On the basis of the simple constraints described here, however, it appears that the effects in terms of extending the time of Columbia Glacier's retreat are moderate and ice flux from the East Basin will be increased only slightly and will likely be short in duration. The principal findings above can be summarized as follows:

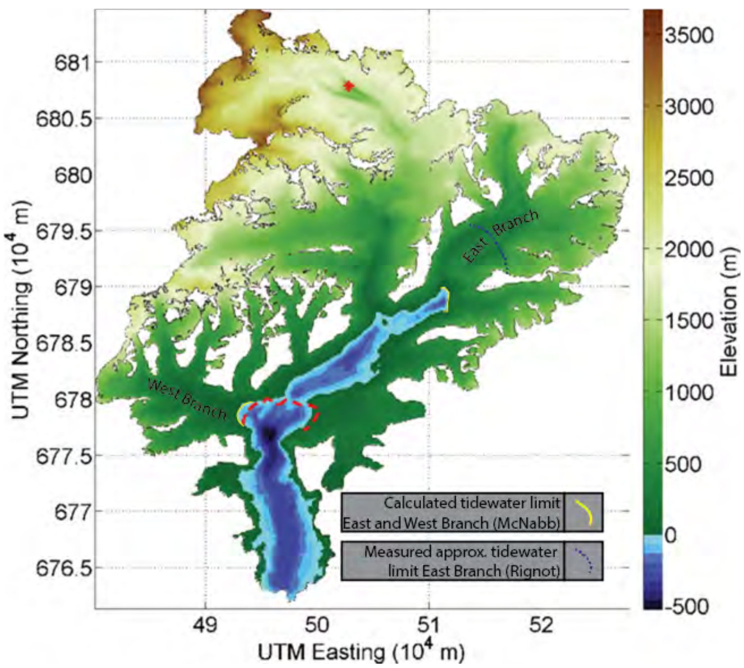
- The ice volume in Columbia Glacier's East Branch is now estimated to be 33 km^3, an increase of ca. 15 km^3 over the ice volume as calculated by McNabb et al (2012).
- At rates of ice flux typical of Columbia Glacier in recent years, the added 15 km^3 will extend the depletion of the East Branch by 7 or 8 years beyond our earlier estimates for this part of the glacier. Note that the retreat of Columbia Glacier's Main Branch may exceed this time; this is not an extension of the overall time to final stability of the entire glacier.
- Assuming a nominal thinning rate of 20 m y^{-1}, the ice thickness in the portions of the East Branch grounded below sea level will reach the critical thickness H_{crit} required for rapid evacuation of ice in approximately 5 years, and rapid evacuation of this additional ice could last as long as 20 years, although depletion of the East Branch reservoir may occur before then.
- Only ca. 0.44 km^3 of ice is located in the deeper portions of the East Branch and below the thickness H_{crit} required for rapid evacuation.
- A very rough estimate of the time to evacuate 0.44 km^3 of ice from the vulnerable portions of the East Branch varies from 3 months to 2 years, with corresponding flux rates ranging from 1.76 to 0.22 km^3 y^{-1}. Again, this timing refers to the East Branch only.

Finally, because of the comparatively thin ice and shallow water in the East Branch, icebergs calved here are likely to be small. This consideration, combined with the fact that the deep basins of the East Branch lie some 15 km upstream from the present terminus position, suggests that any icebergs calved during rapid evacuation of the East Branch basin will be very small or may have melted altogether by they time they reach the Heather Bay Moraine Shoal. The ultimate effects on iceberg hazards in Columbia Bay as therefore probably minimal. One important aspect that should be considered further, however, is the potential for the East Branch to produce bergs in the growler-and-smaller size classes for an extended period at some point, possibly 5 to 15 years in the future.

References

Rignot, E., Mouginot, J., Larsen, C. F., Gim, Y., & Kirchner, D. (2013). Low-frequency radar sounding of temperate ice masses in Southern Alaska. Geophysical Research Letters, 40(20), 5399–5405. doi:10.1002/2013GL057452

Mcnabb, R. W., Hock, R., O'Neel, S., Rasmussen, L. A., Ahn, Y., Braun, M., Conway, H., Herried, S., Joughin, I., Pfeffer, W.T., Smith, B., and Truffer, M. (2012). Using surface velocities to calculate ice thickness and bed topography: a case study at Columbia Glacier, Alaska, USA. Journal of Glaciology, 58(212), 1151–1164. doi:10.3189/2012JoG11J249



adapted from McNabb et al (2012)

Figure 1: McNabb Calculated Bed – Calculated bed topography from McNabb et al. (2012) showing tidewater limits from both McNabb and Rignot (2013).

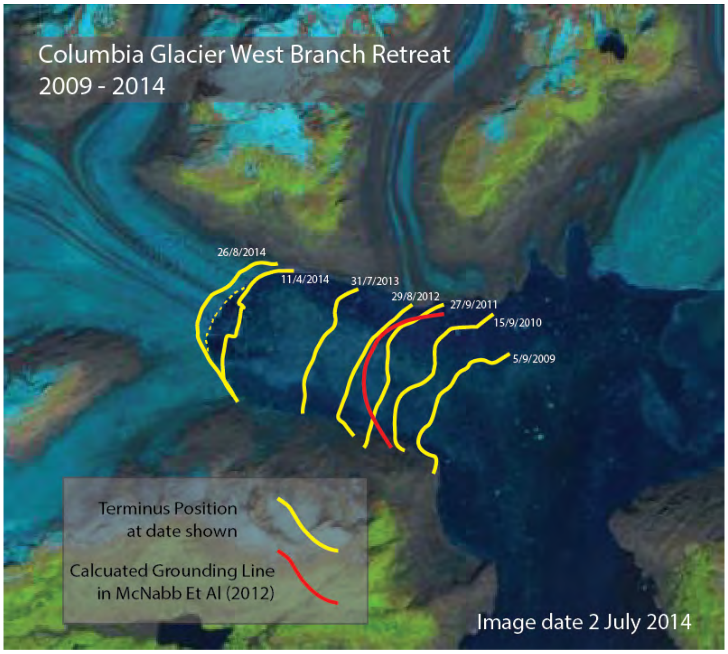


Figure 2: West Branch Retreat – Positions of the West Branch terminus 2009-2014, in yellow, extending well past the grounding line as calculated by McNabb et al. (2012), in red.

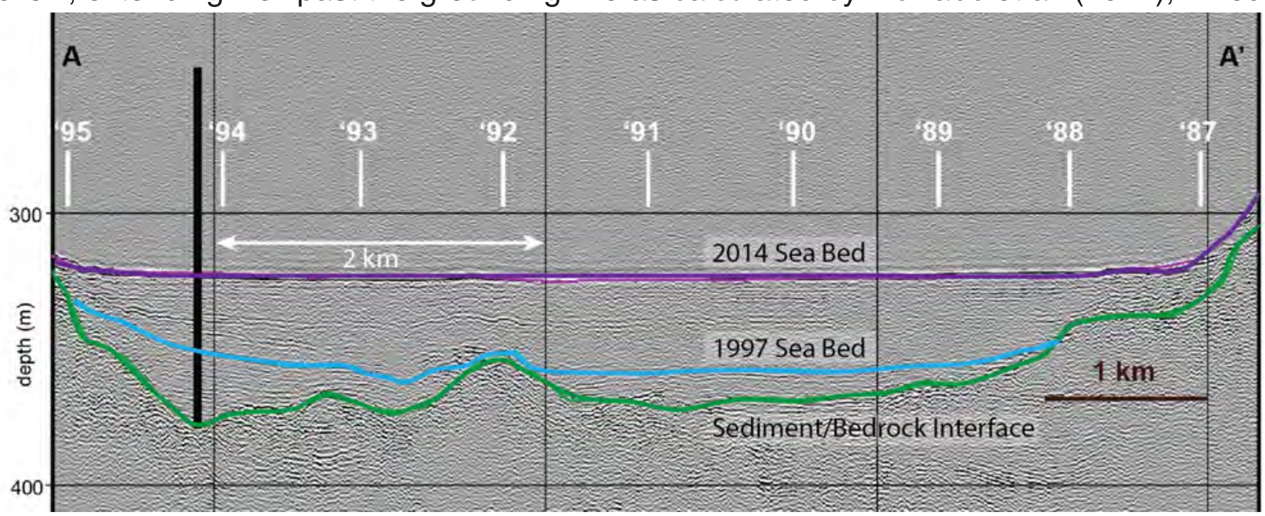


Figure 3: Forebay Sediment – Elevation of the bed (the water-sediment interface) in 1997 and at present (~ 2011), and the sediment-bedrock interface according to seismic surveys by K. Boldt and colleagues from the University of Washington in 2011. The profile runs down the main channel from just seaward of the Kadin-Great Nunatak Gap to the pre-retreat terminus.

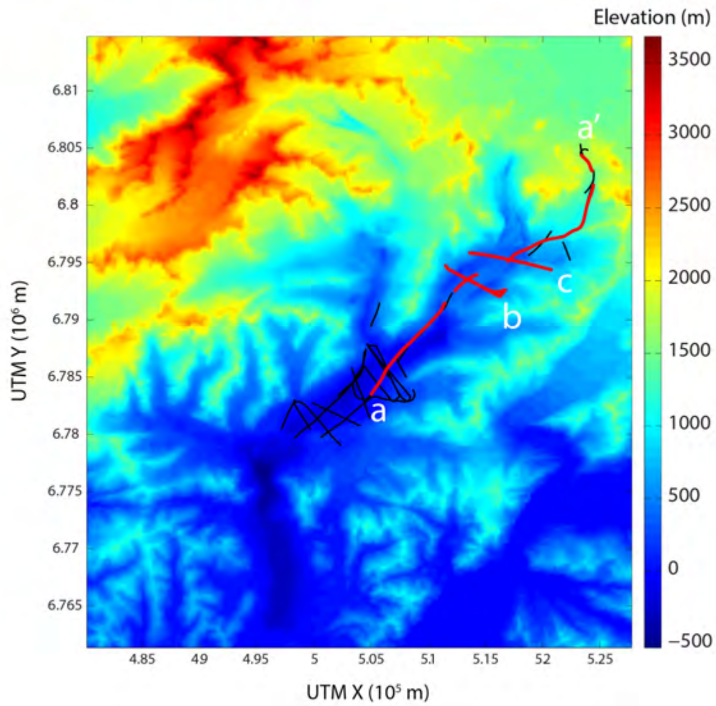


Figure 4: Radar Flight Lines – Warm Ice Sounding Explorer (WISE) radar flight lines from Rignot et al. (2013) on a map of calculated bed elevations from McNabb et al. (2012). The red highlighted profiles are those of (a), (b), and (c) plotted in Figure 5.

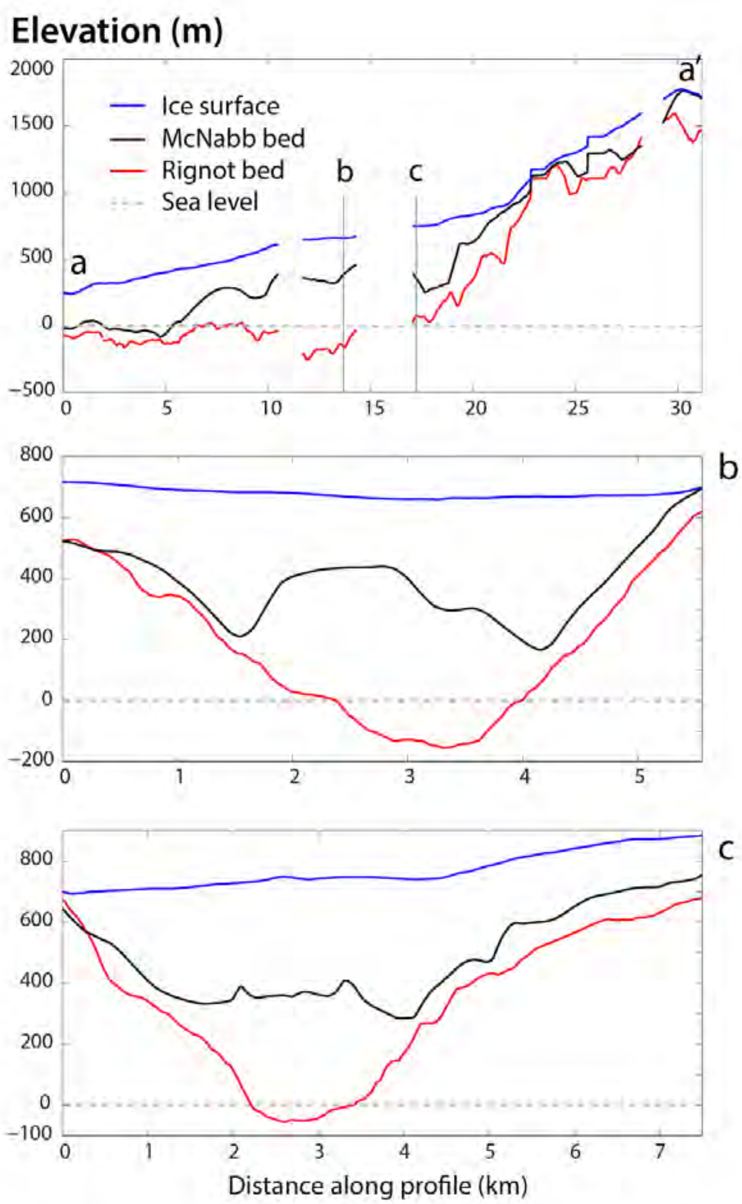


Figure 5: Radar Profiles – Radar (Rignot et al. 2013) and modeled (McNabb et al. 2012) bed elevations plotted alongside ice surface elevation and sea level for the profiles (a), (b), and (c) shown in Figure 4.

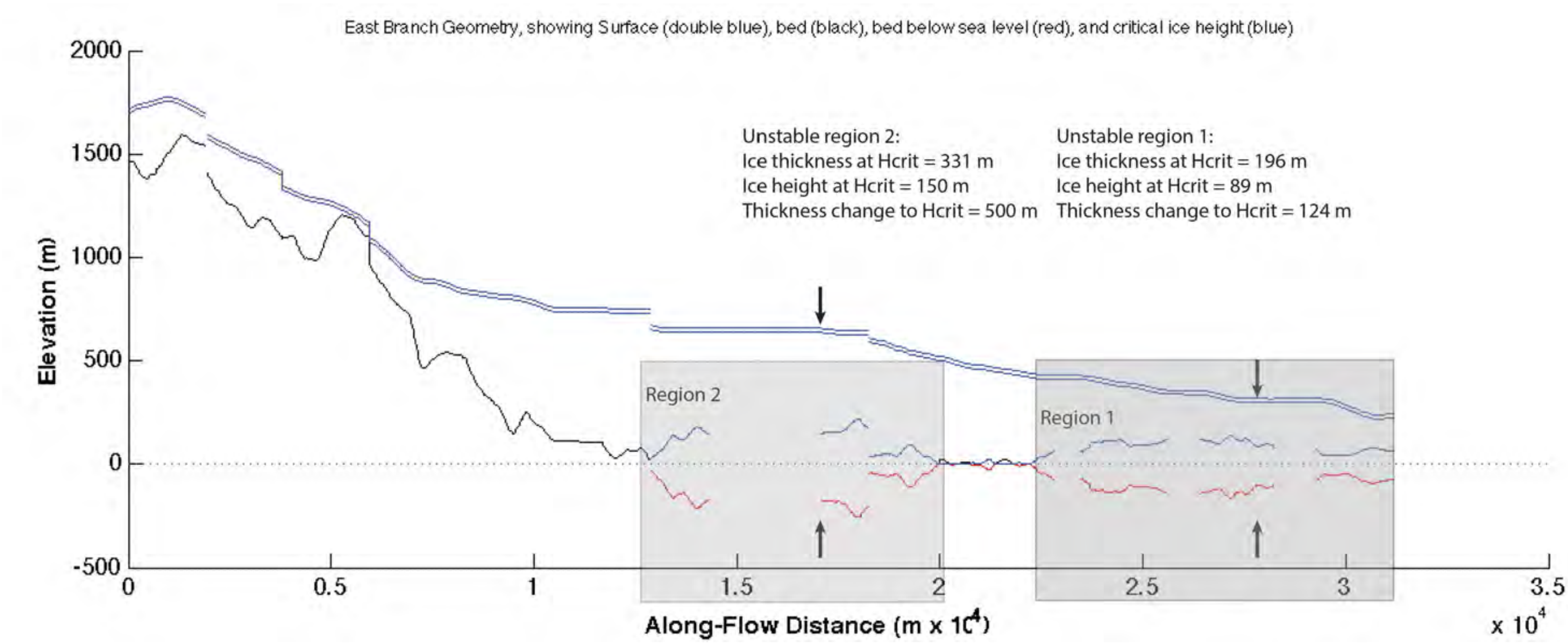


Figure 6: Geometry of East Branch along a-a' transect (Figures 3 and 4). The bed elevation falls below sea level in regions 1 and 2, allowing unstable retreat to occur here. The critical thickness for instable retreat, h_{crit}, is a function of water depth, and is plotted as the blue dotted line in the two regions. Important representative values for the two regions are shown.