ESS 203 - Glaciers and Global Change

Wednesday March 10, 2021.

Outline for today

- Today's highlights on Friday – *Jennifer Lomeli*
- Last Monday's highlights – *Alex Kissel*

Last Monday

- We looked into glacier surging, and had a preliminary look at the Tidewater Glacier Cycle.

Today

- More on the Tidewater Glacier Cycle.
- Potential instability of the West Antarctic Ice Sheet (WAIS).

HW 27 – due Friday March 12

For Friday, please read Chapter 12 in *Frozen Earth,* p. 232-244, "Ice ages and the future".

In about a page, describe your expectations about ice on Earth in 10 years, in 100 years, in 1000 years, and in 10,000 years.

Course/Instructor Evaluations

I expect you have received course-evaluation requests from IAS (UW Instructional Assessment Surveys).

These evaluations help us to improve our teaching and to design courses to be more effective, and they allow you to pass forward your insights to future students.

We hope you will participate in 3 anonymous surveys, to assess:

1. Ed's contributions (lectures, and the course as a whole).

   https://uw.iasystem.org/survey/239461

2. Seth's contributions (Labs and lecture).

   (see your email or ask Seth for the link)

3. Jessica's contributions (Lectures and your group projects).

   (see your email or ask Jessica for the link)

We know that is takes time to complete not 1, but 3 surveys, and we (and future students) all appreciate your time and contributions ☺

Thanks!

The surveys will be open until Friday next week Mar 19, 2021 at 11:59pm.

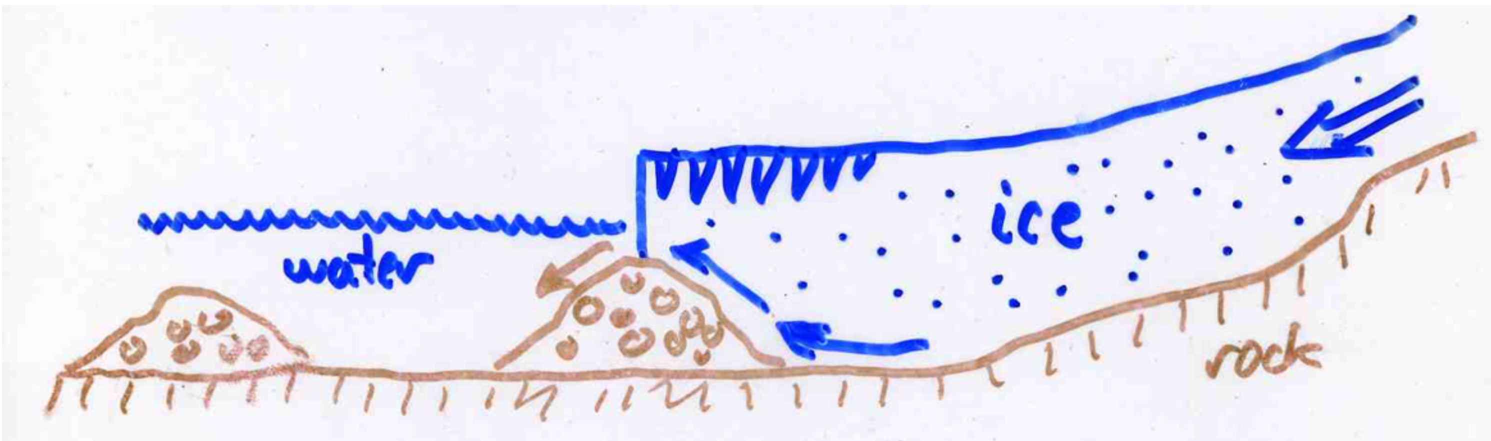
Tidewater Glaciers

- Terminus is in ocean
- Terminus is grounded, not floating
- Glaciers advance and retreat over time scales of a century.

- These are not surge-type glaciers (i.e. not controlled by bed changes).
- Yet cycle is not closely tied to climate changes on the surface either …

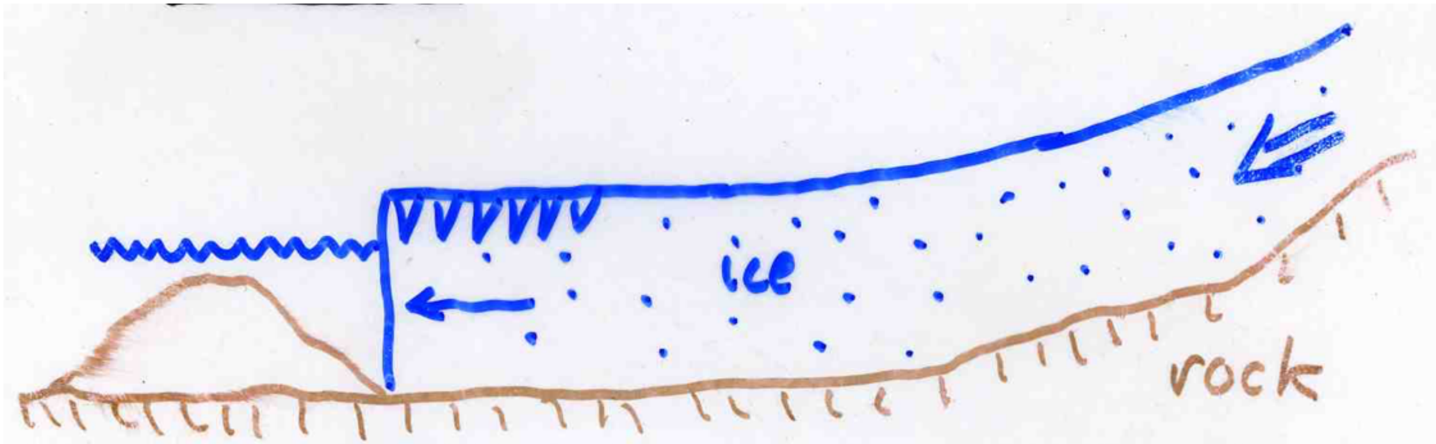
Columbia Glacier AK
June 2005 W.Tad Pfeffer

Tidewater Glaciers – the Advance



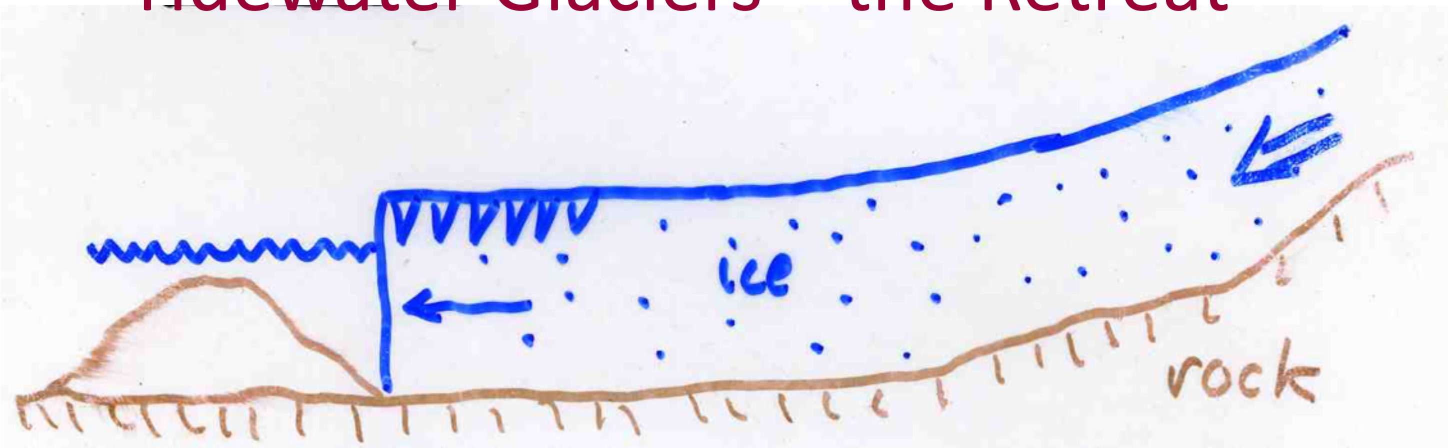
- Glacier advances along a fiord
- Subglacial rivers build a moraine shoal or delta in front
- Shoal protects glacier terminus from sea water

Tidewater Glaciers – the Critical Moment



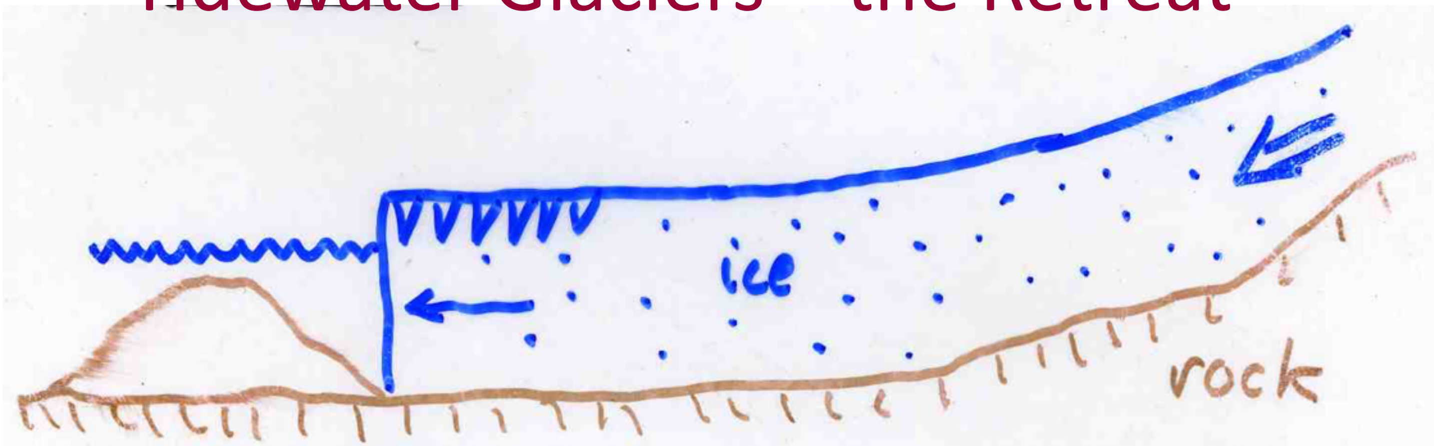
- Glacier retreats just a little from the shoal
- (this could be result of a minor climate change).
- Seawater can now get at the terminus to melt and undermine it.
- Water deepens as glacier retreats into glacially scoured fiord.

Tidewater Glaciers – the Retreat

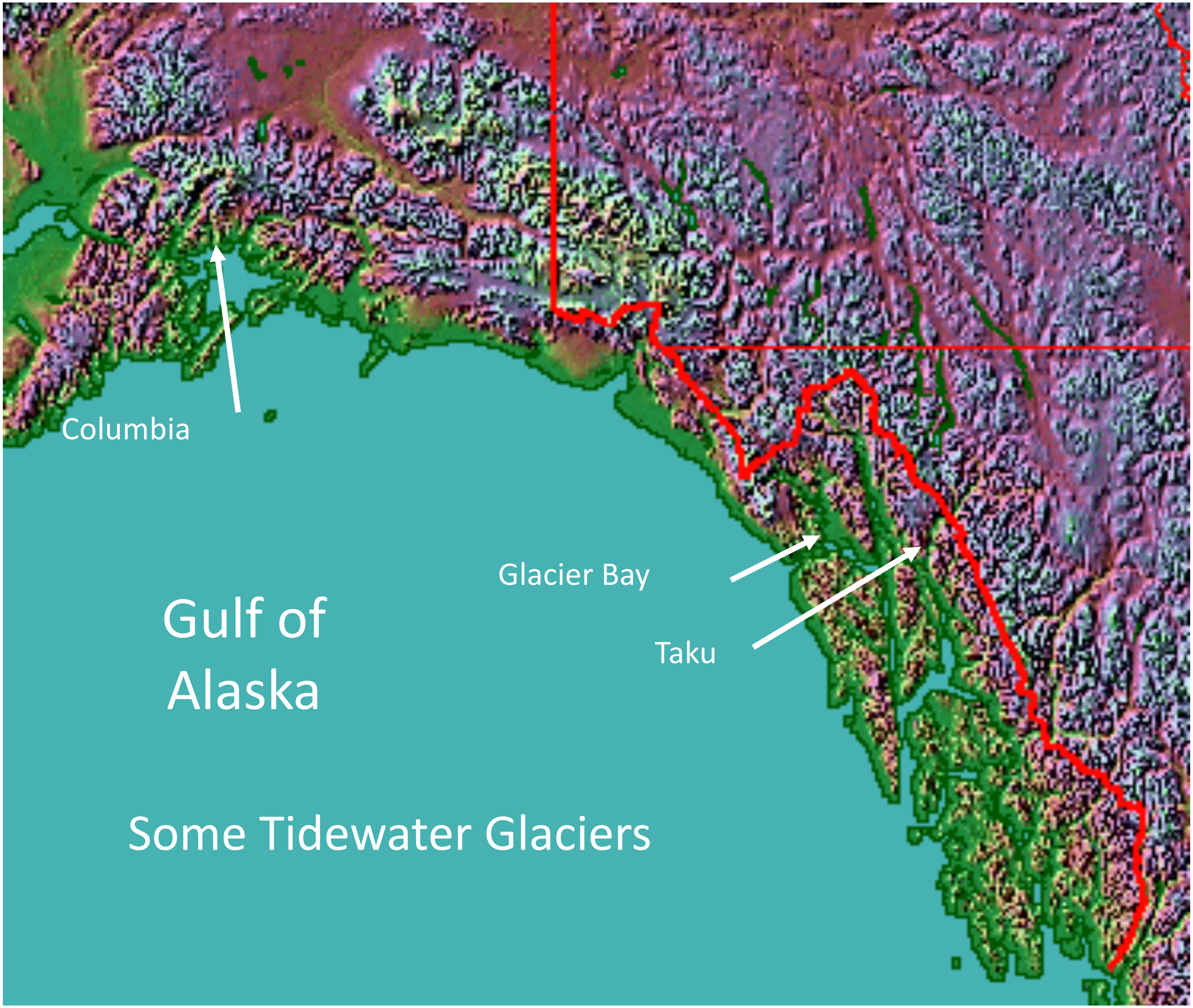


- Water deepens as glacier retreats into glacially scoured fiord.
- Calving rate increases rapidly with water depth.
- Retreat accelerates.
- There is no going back to the moraine shoal.
- Glacier must retreat all the way back to dry land.
- Only then can it can start another advance, with its terminus protected by a new moraine shoal.

Tidewater Glaciers – the Retreat

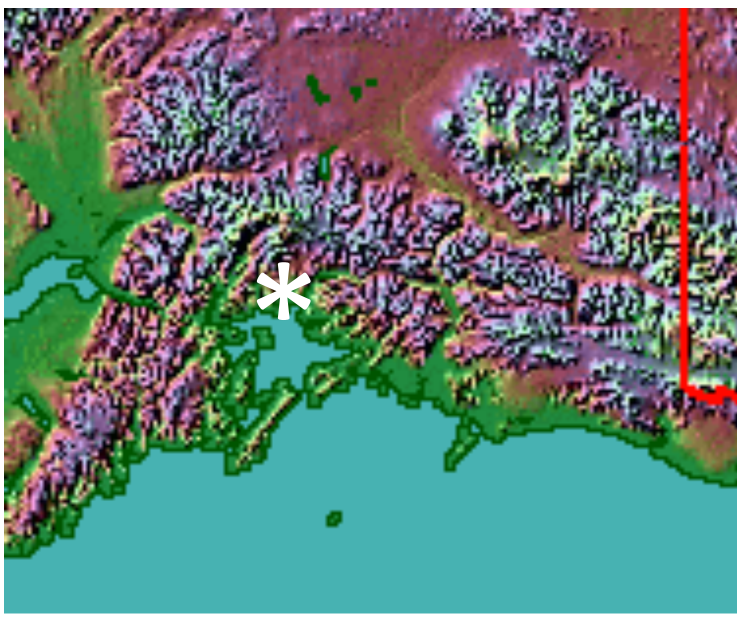


- Retreat is initiated by climate changes.
- But glacier response (retreat) is strongly amplified by tidewater physics.

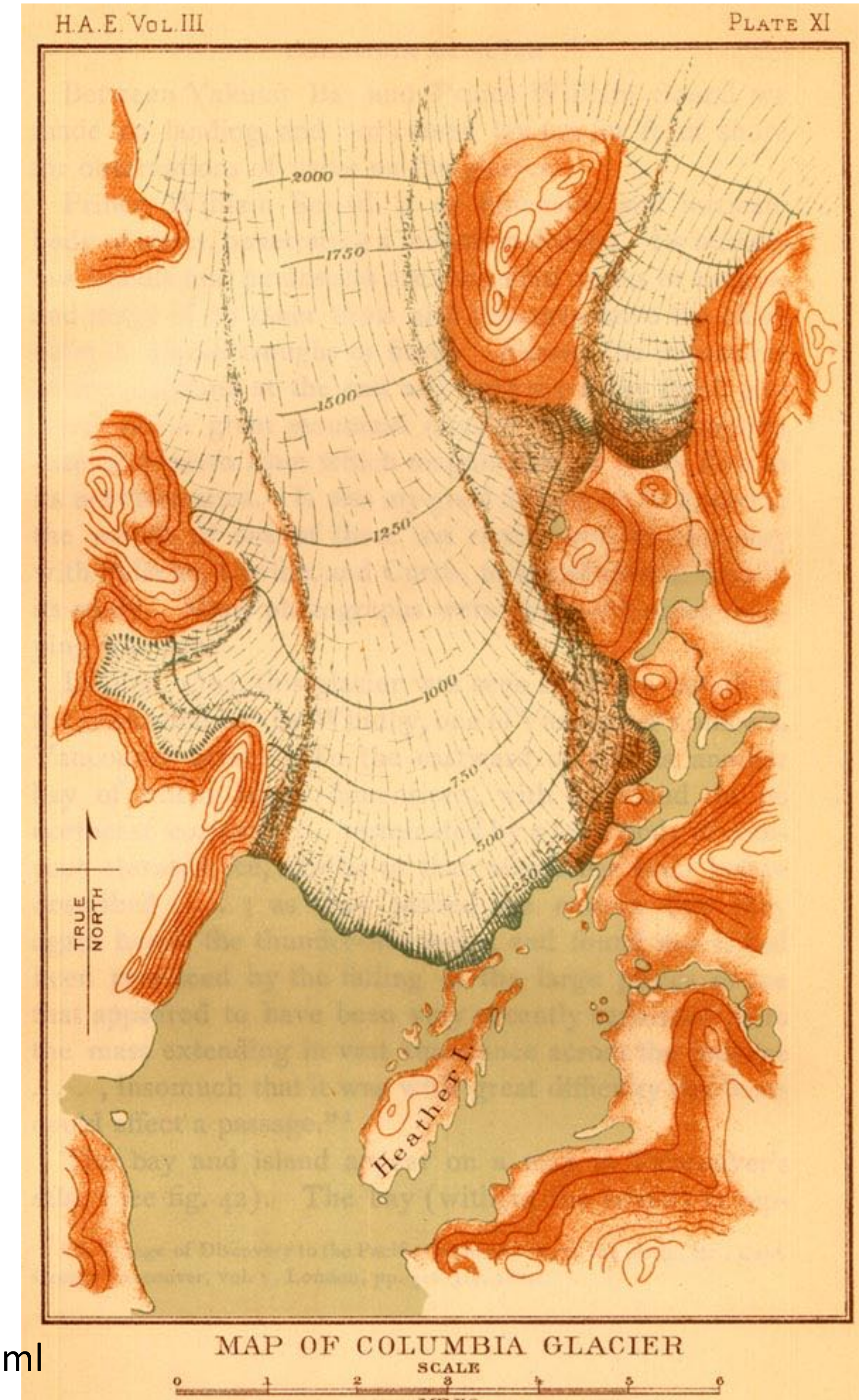

Columbia
Glacier Bay
Taku
Gulf of Alaska
Some Tidewater Glaciers

Columbia Glacier 1899
Harriman Expedition

Terminus was on a shoal near Heather Island



http://www.pbs.org/harriman/maps/historic_maps.html



Columbia Glacier 1979

Terminus was still on the shoal near Heather Island in 1979, 80 years later.

Austin Post 1979

Columbia Glacier

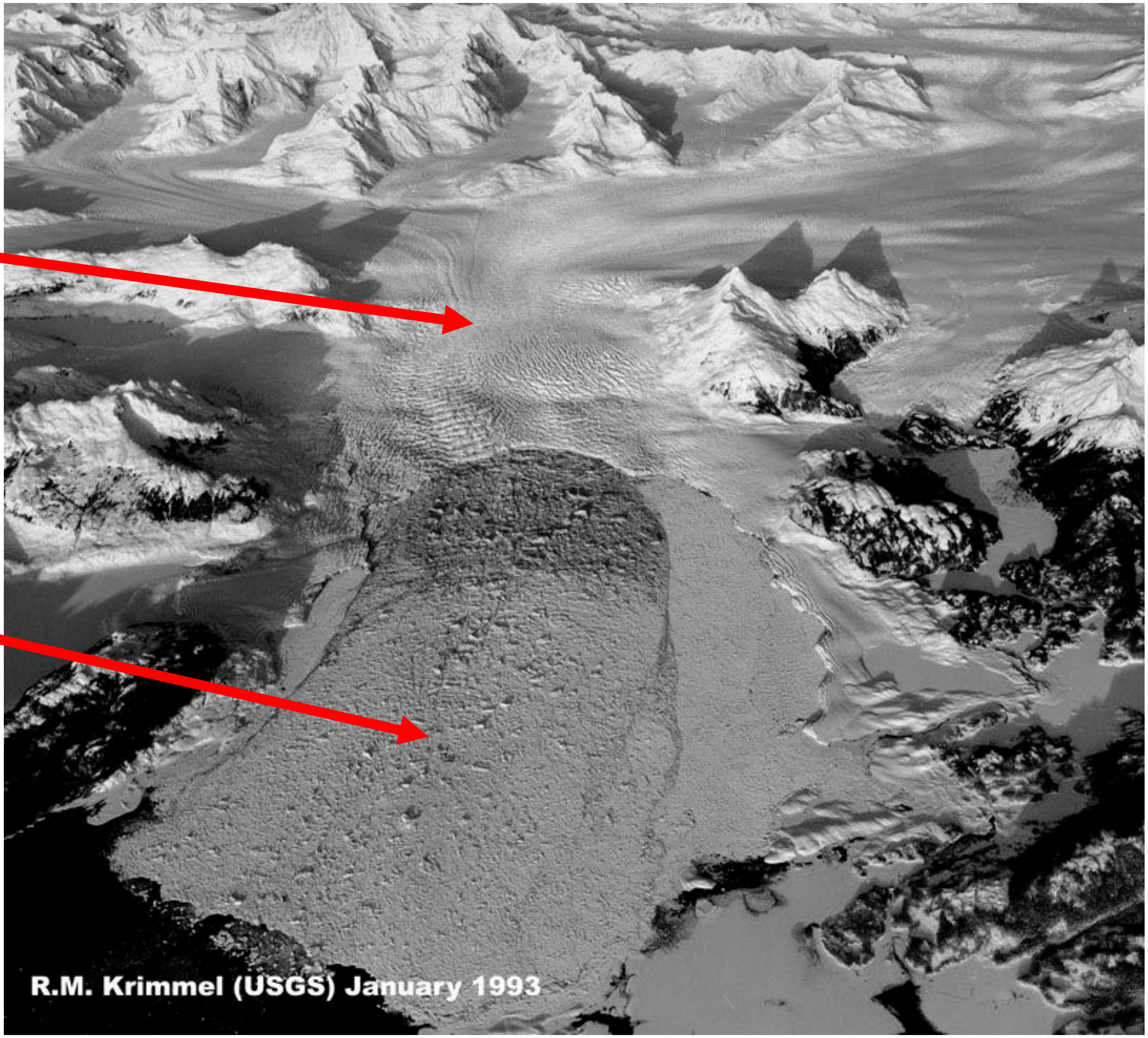
- Retreat from Heather Island began in 1982, just as North Slope oil began to ship from Port Valdez.

- Tanker Exxon Valdez was taking a course to avoid small icebergs from Columbia Glacier when it went aground on Bligh Reef (named after Bligh of *Mutiny on the Bounty* fame).

Columbia Glacier 1993

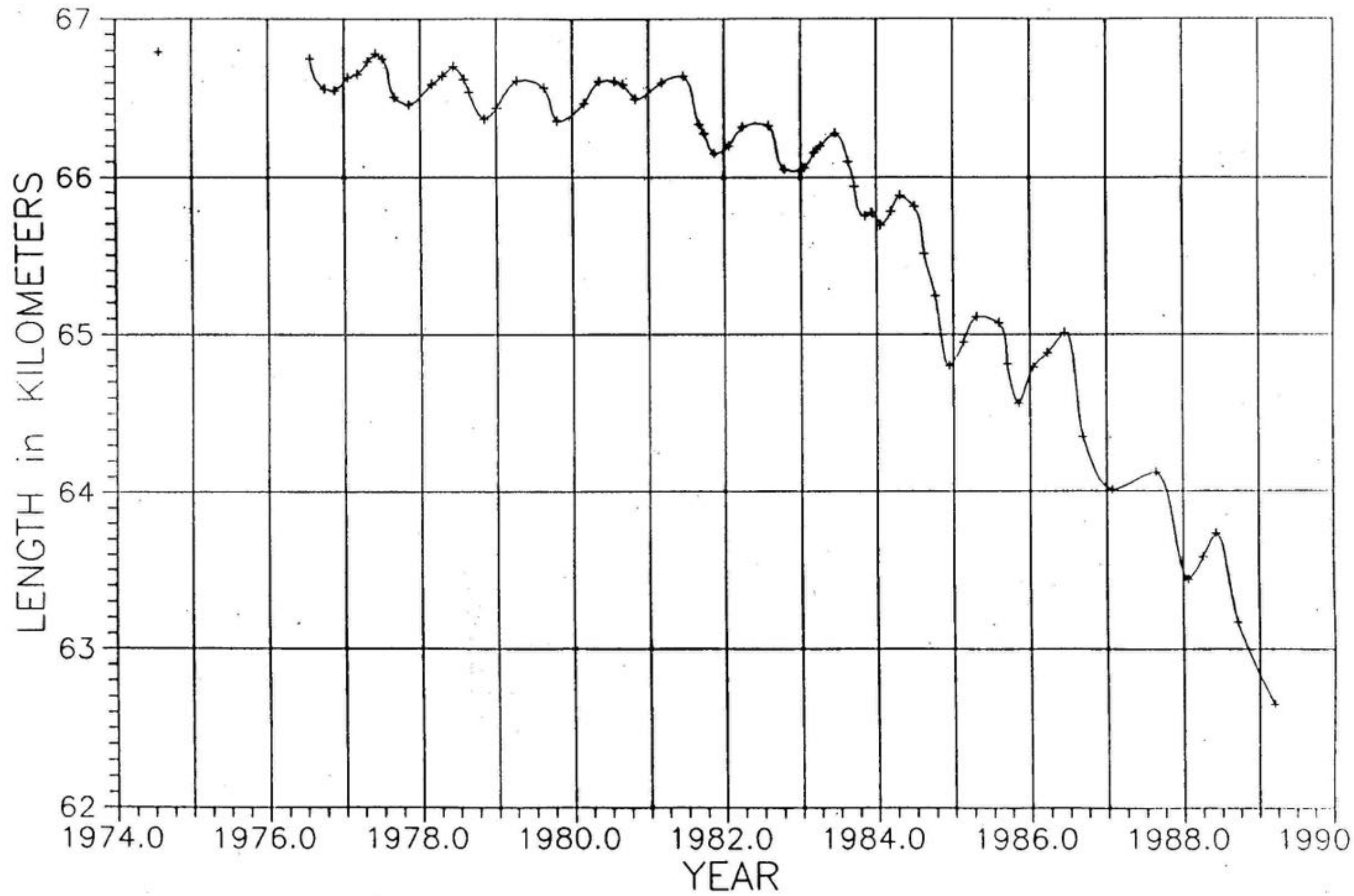
Terminus was back almost to Kadin-Great Nunatak Gap by 1993.

- Larger icebergs are trapped in the bay by the shoal at Heather Island.



Bob Krimmel 1993

Columbia Glacier – the retreat begins



- Glacier retreated 4 km in first 7 years
- Similar rate was maintained into the 1990s.

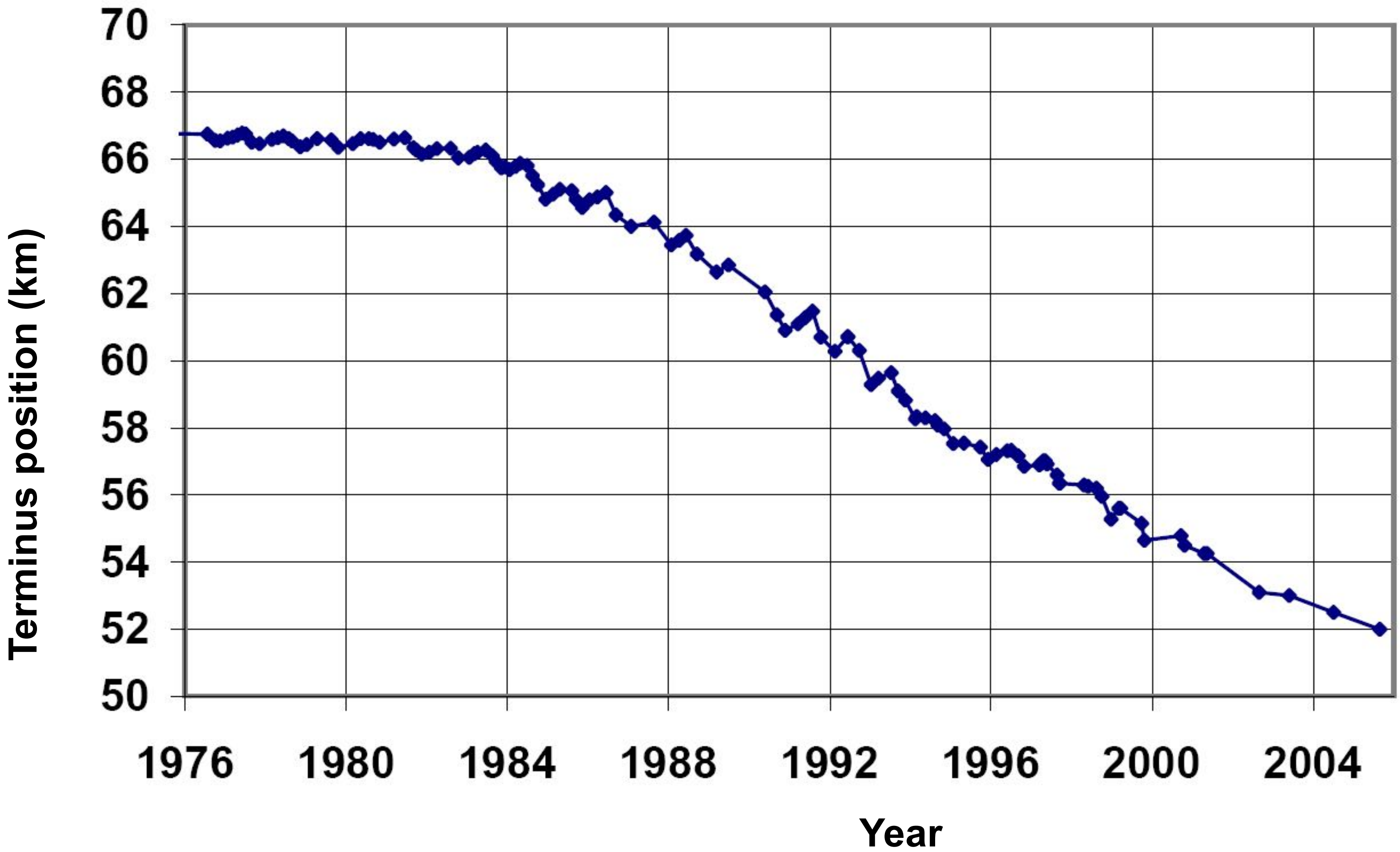
Columbia Glacier 2004

Terminus was in the Kadin-Great Nunatak Gap by 2004.

- Terminus had retreated 15 km.
- Ice was moving at ~10 km/yr at terminus.

W. Tad Pfeffer 2004

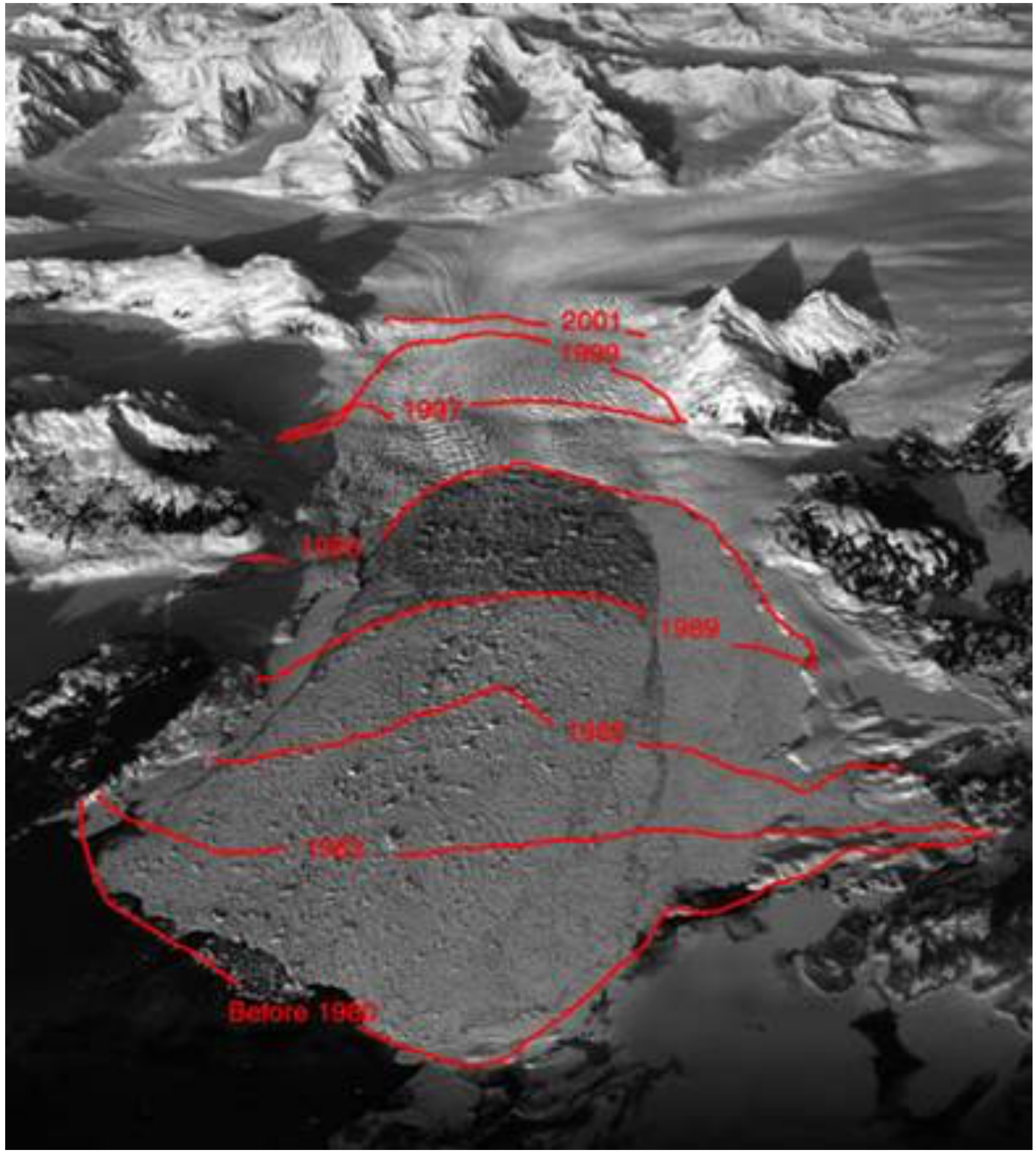
Columbia Glacier Retreat 1980-2005



http://tintin.colorado.edu/

Columbia Glacier Retreat 1980-2001

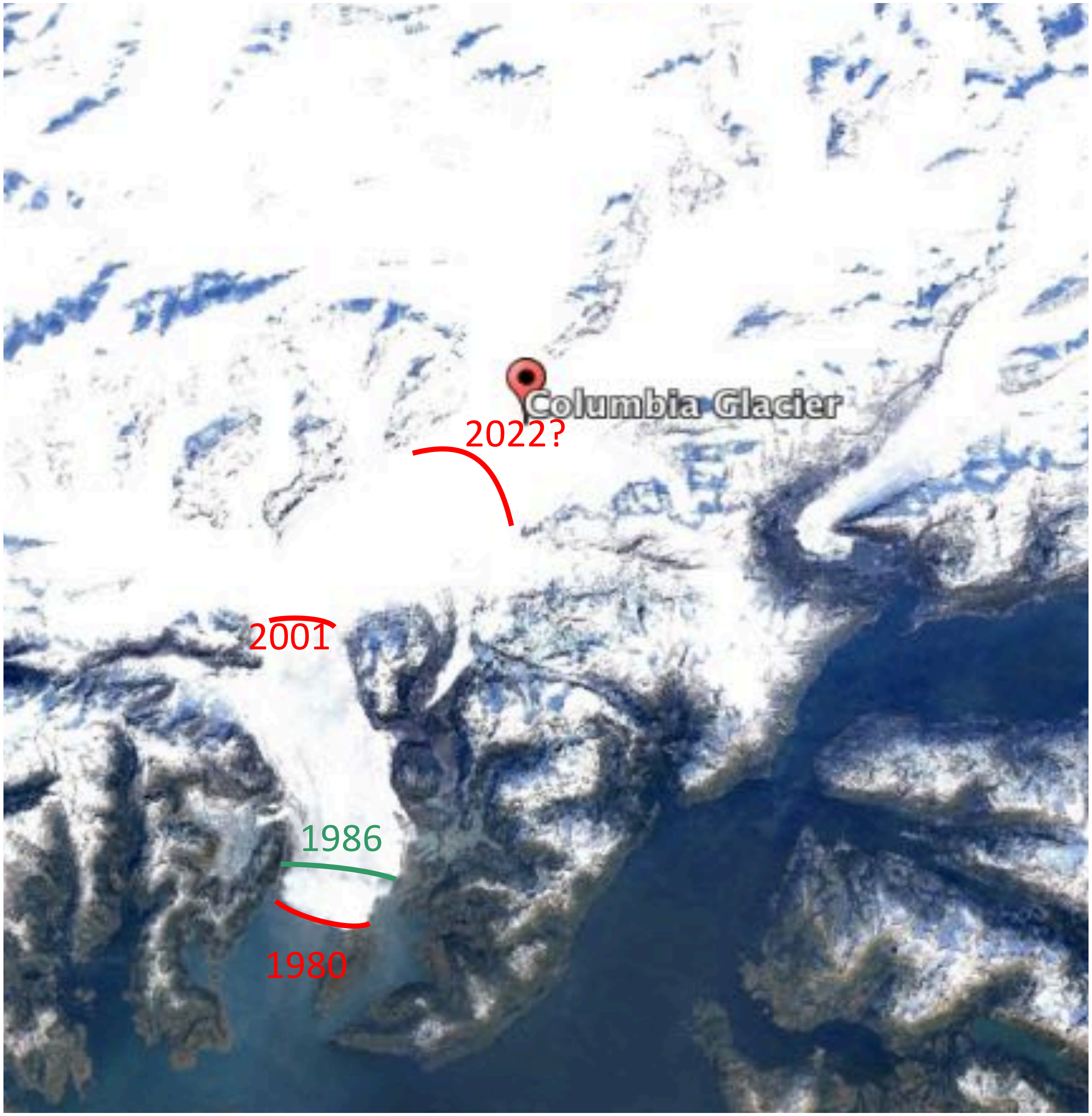
- Retreated >15 km
- Bed does not reach sea level until 15 km upstream



http://tintin.colorado.edu/group/columbia/SciObj.html

Columbia Glacier
Sept 1986

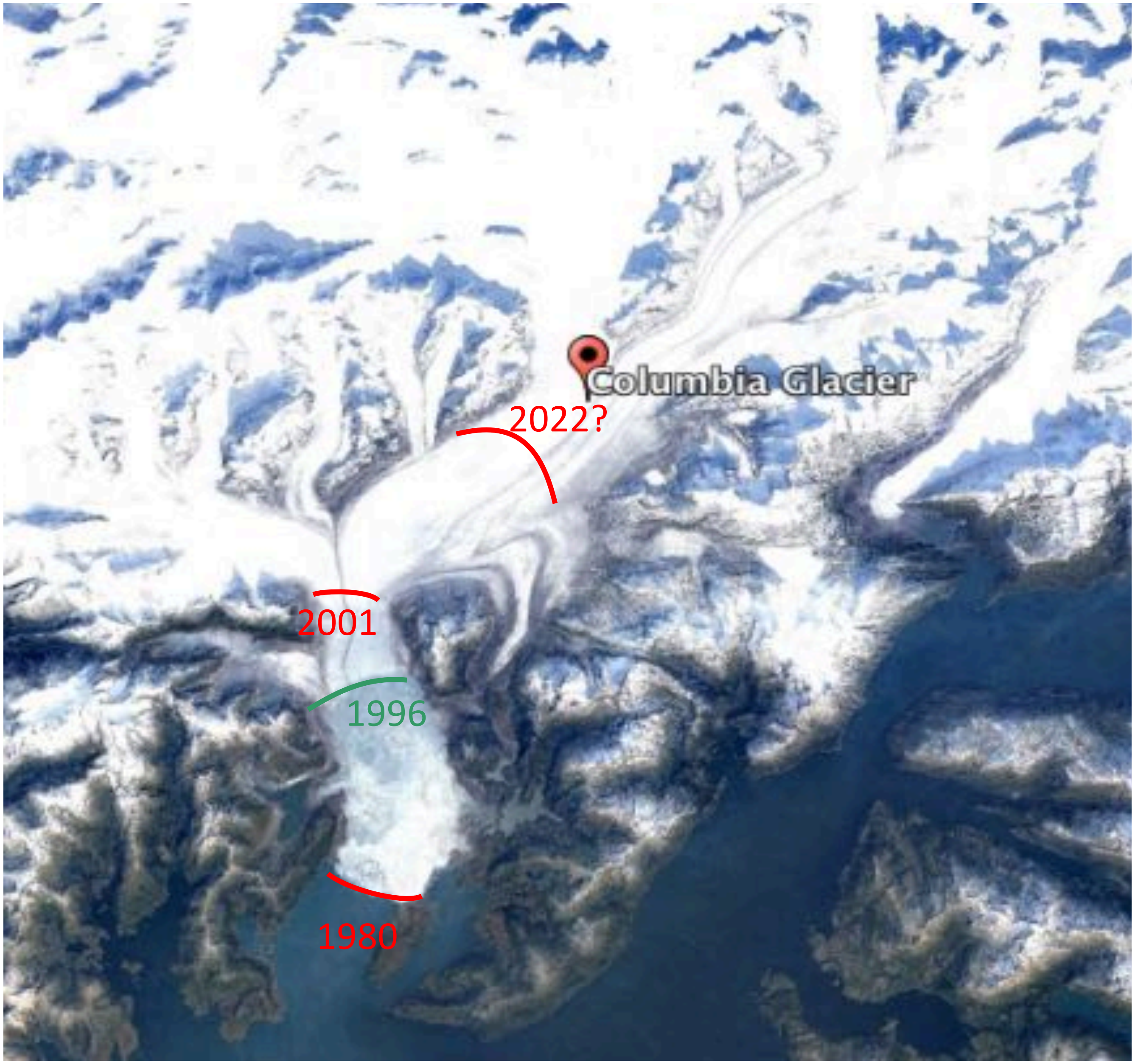
- Retreated several km
- Moraine traps bigger icebergs



Google Earth

Columbia Glacier
Sept 1996

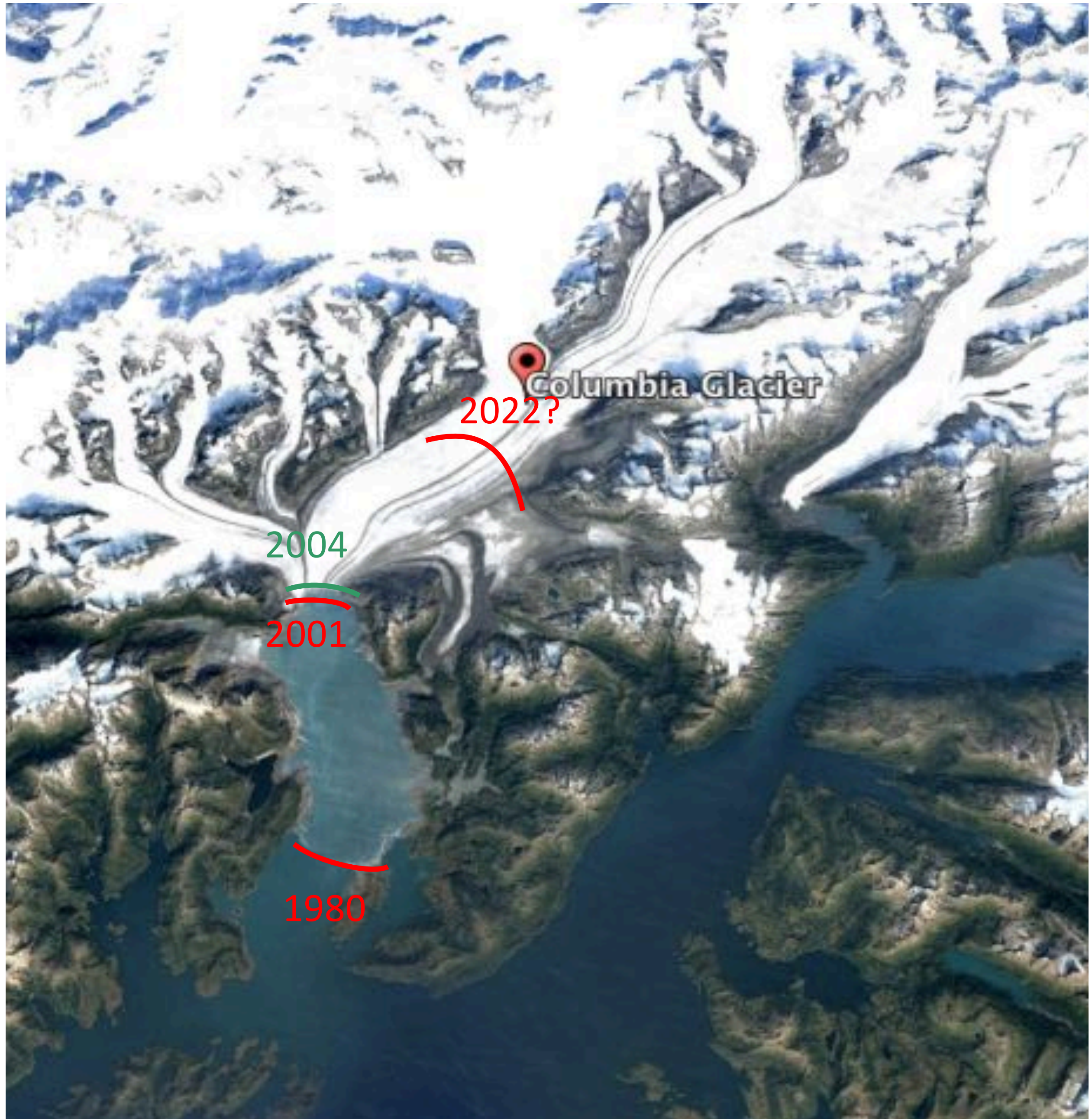
- Still retreating rapidly.



Google Earth

Columbia Glacier
Sept 2004

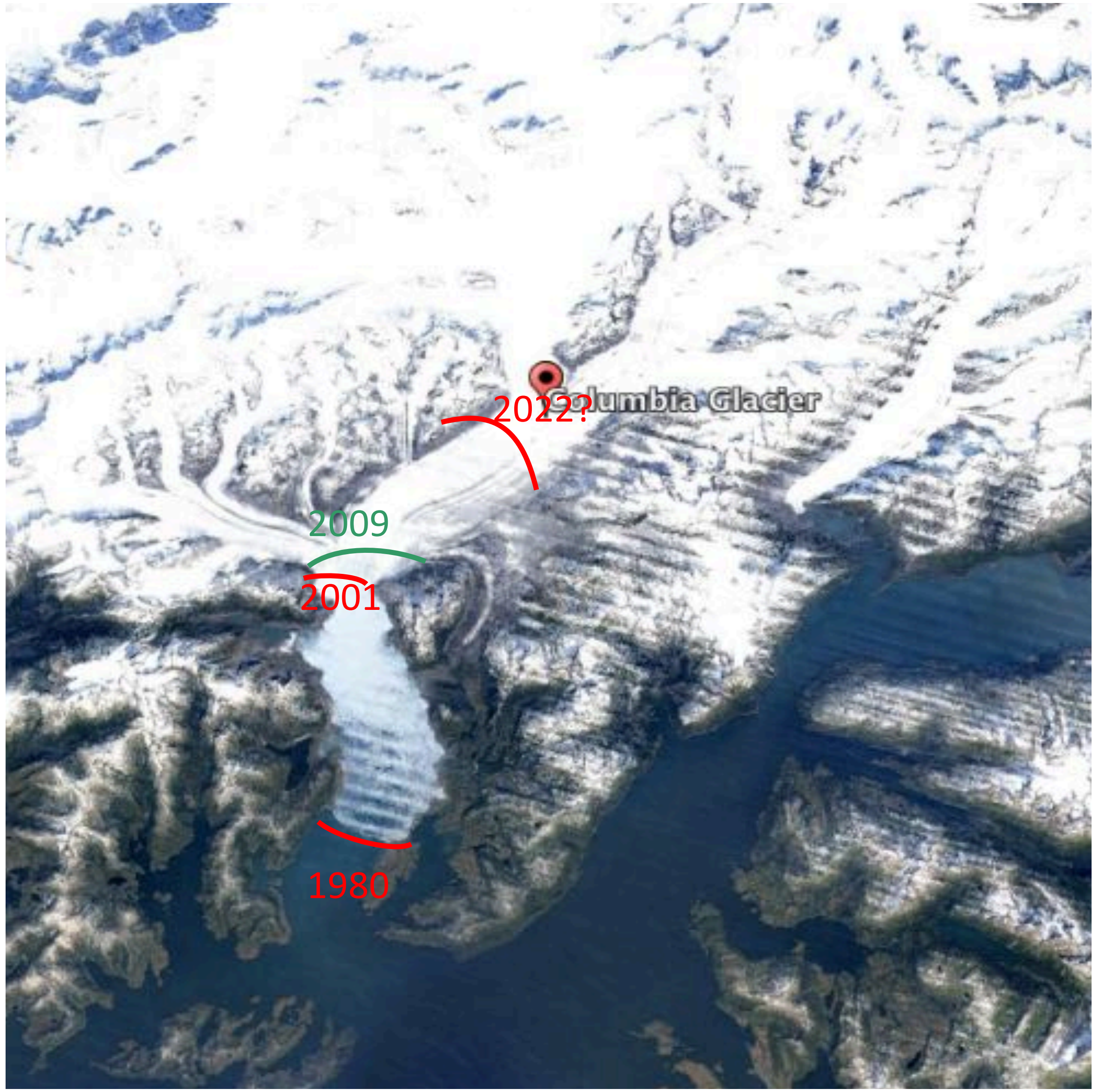
- Retreat slowed down getting through narrow gap at Great Nunatak



Google Earth

Columbia Glacier
Sept 2009

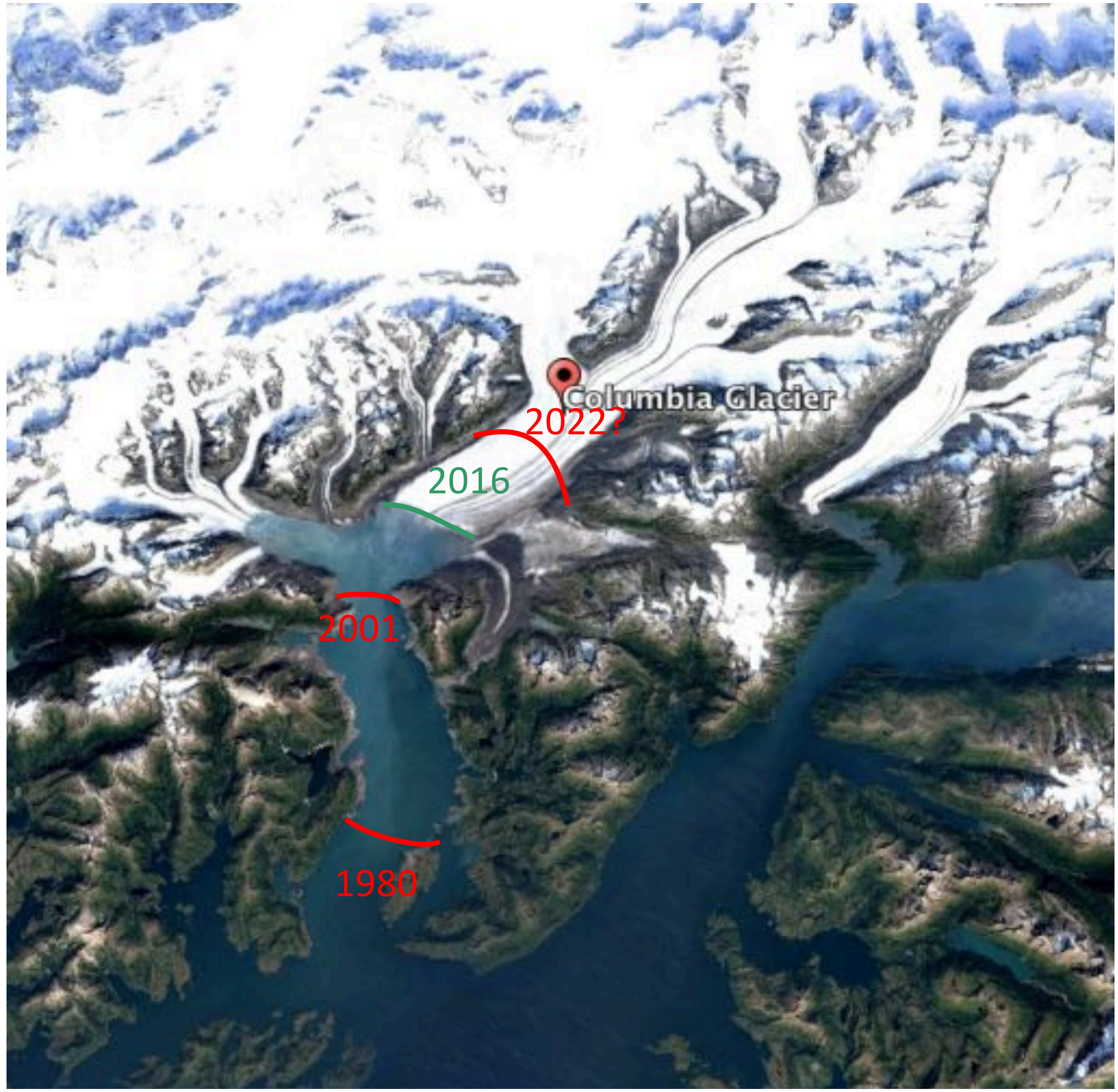
- Retreat speeded up again.
- 2 tributaries are now separated.



Google Earth

Columbia Glacier
Sept 2016

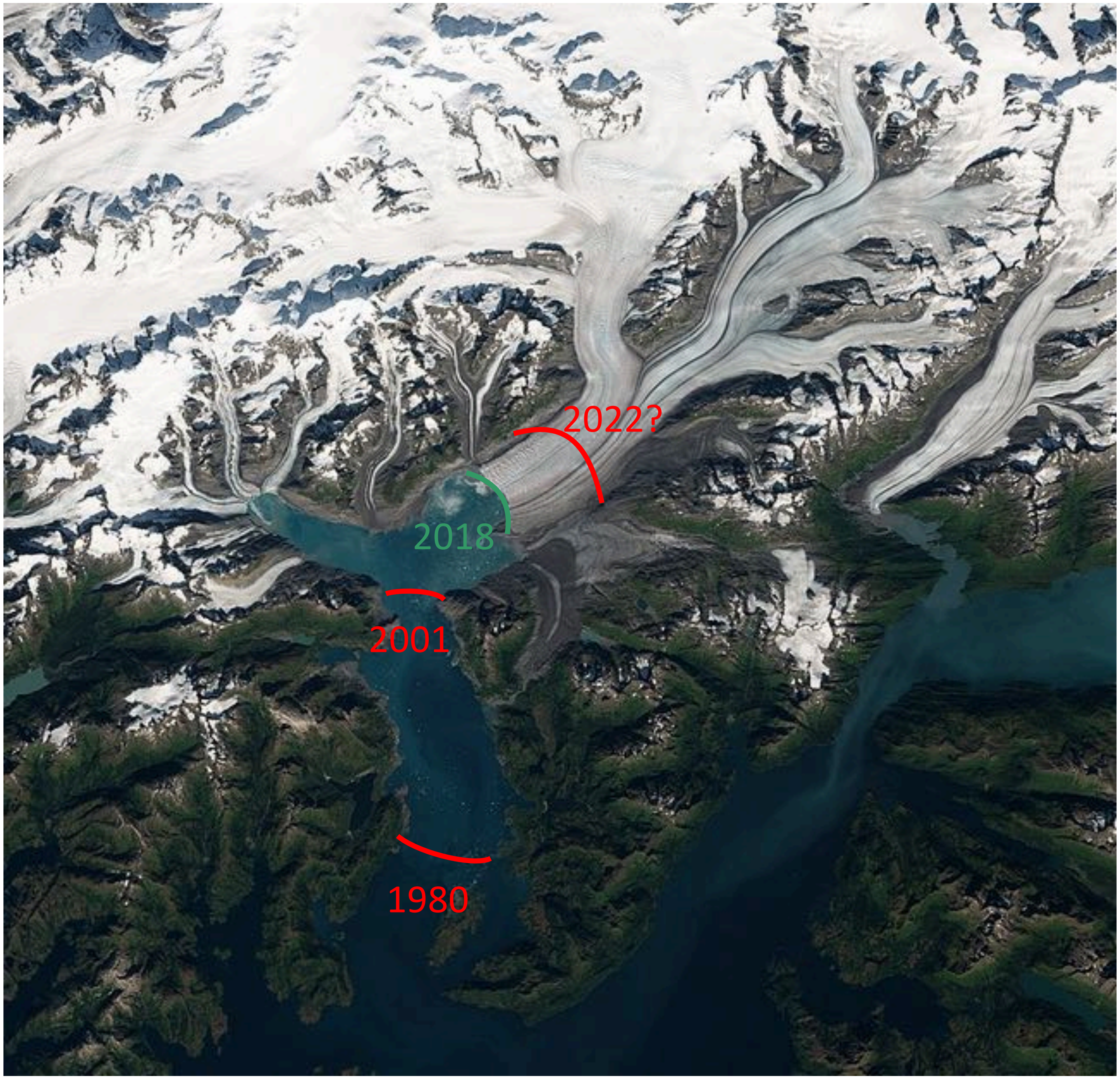
- Retreat slowing down again.
- Bed elevation is closer to sea level.



Google Earth

Columbia Glacier
Sept 2018

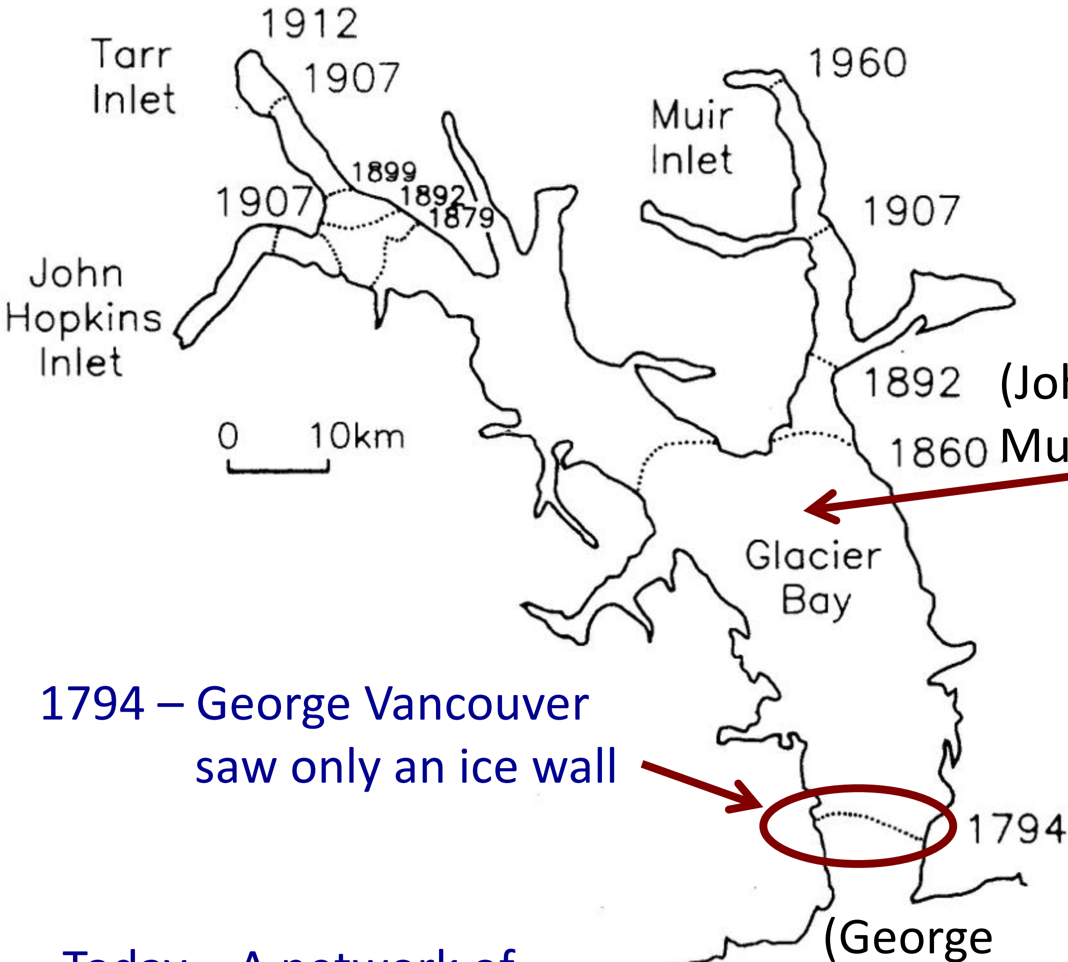
- Retreating very slowly.
- Expected to stop in the next few years, where bed reaches sea level.



Google Earth

Glacier Bay

- Glaciers have been retreating for over 200 years.



(John Muir)

(George Vancouver)

1869 – John Muir found one large bay

1794 – George Vancouver saw only an ice wall

Today – A network of glacier fiords

Google Earth

Glacier Bay Today

150 km of cruise-ship delights …

Glacier Bay in the Future

Barring major climate changes, the glaciers will advance again.

• Note the sediment delta in Queen Inlet in front of Carroll Glacier

Taku Glacier – the advance

- Taku Glacier is 30 km from Juneau (Alaska state capital)
- Taku Glacier sends high sediment load Taku Inlet.
- Early in the 20^{th} C, lumber ships navigated up Taku Inlet, past Taku Glacier, to pick up logs.
- For 100 years, Taku Glacier advanced over a braided-stream flood-plain that eventually closed off Taku Inlet.
- The advance has now stopped.

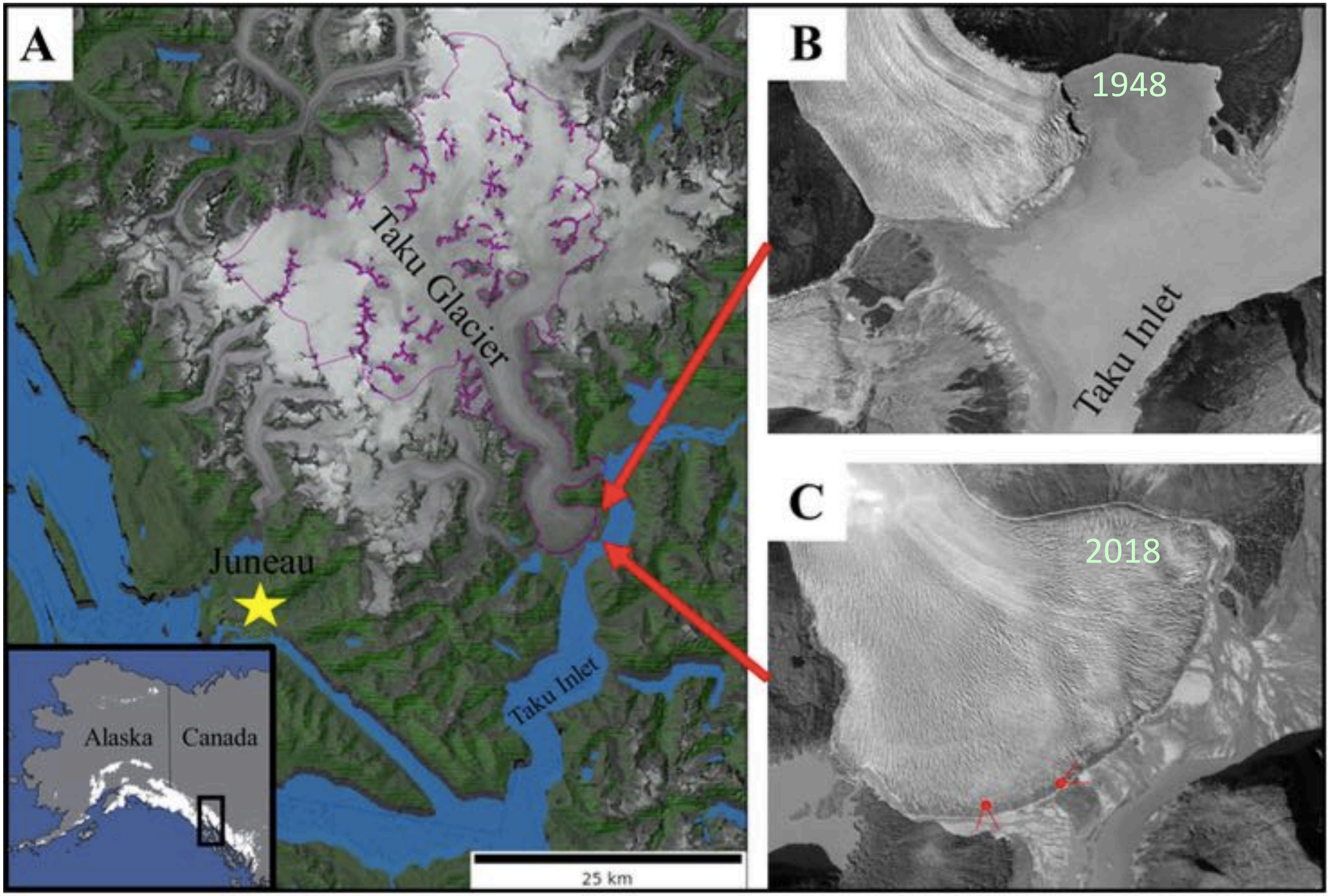
Taku Glacier advances as Taku Inlet fills with sediment

NASA WorldWind Landsat7

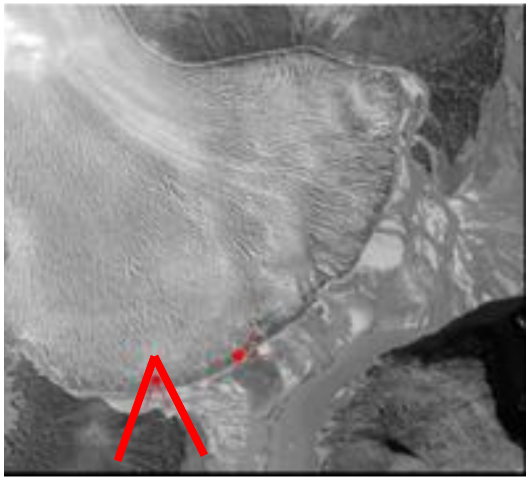
August 2019. Matt Nolan

https://eos.org/science-updates/the-imminent-calving-retreat-of-taku-glacier

The advance

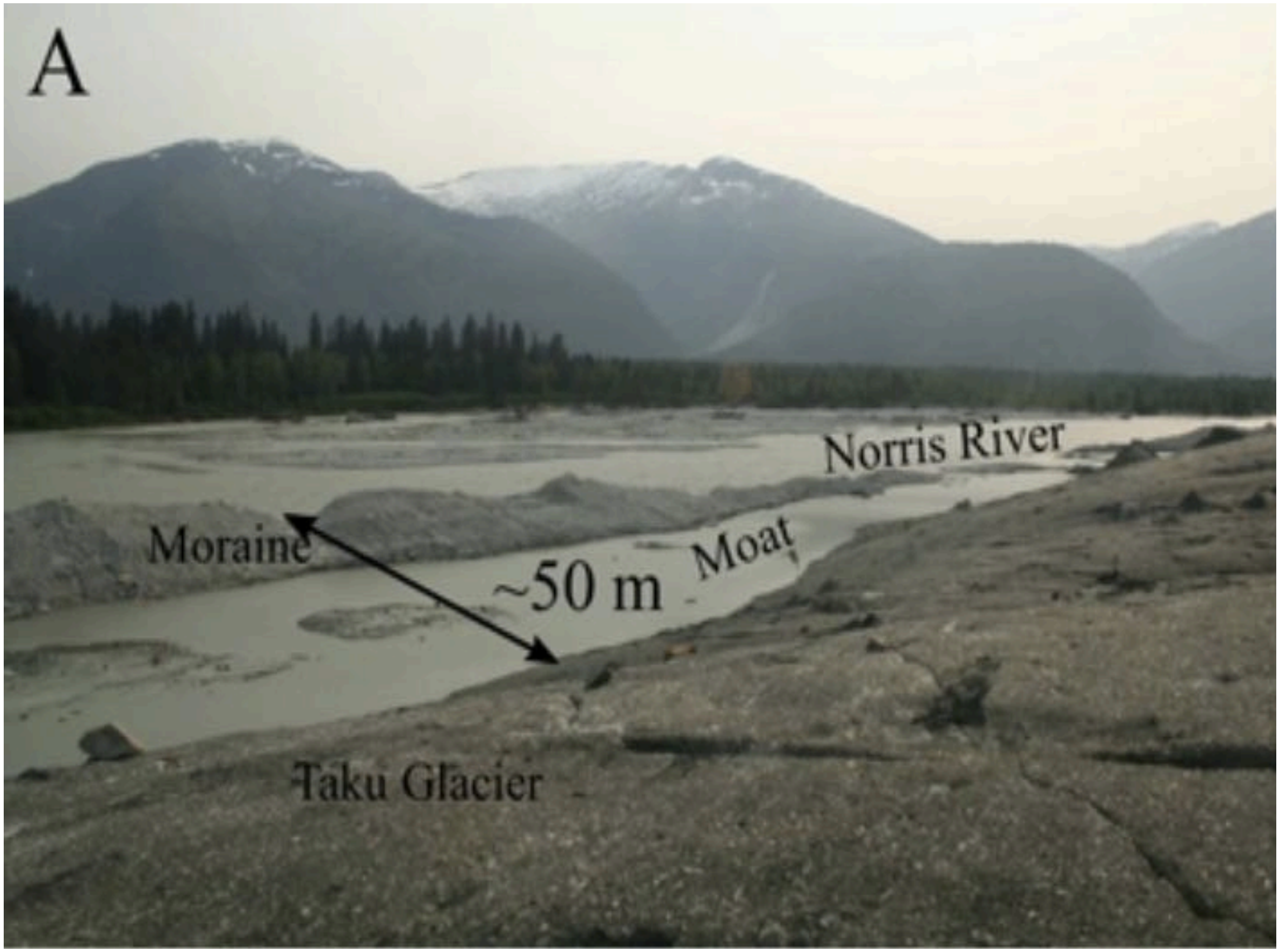


https://eos.org/science-updates/the-imminent-calving-retreat-of-taku-glacier



Camera view

Advance has slowed since 1980

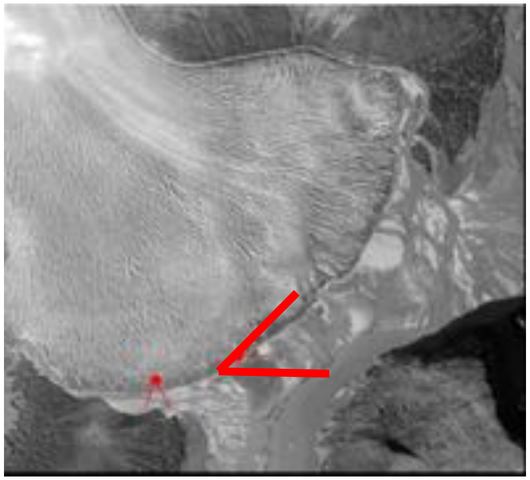


Retreat phase appears to have begun in 2018.

- A moat has opened in front of the glacier.

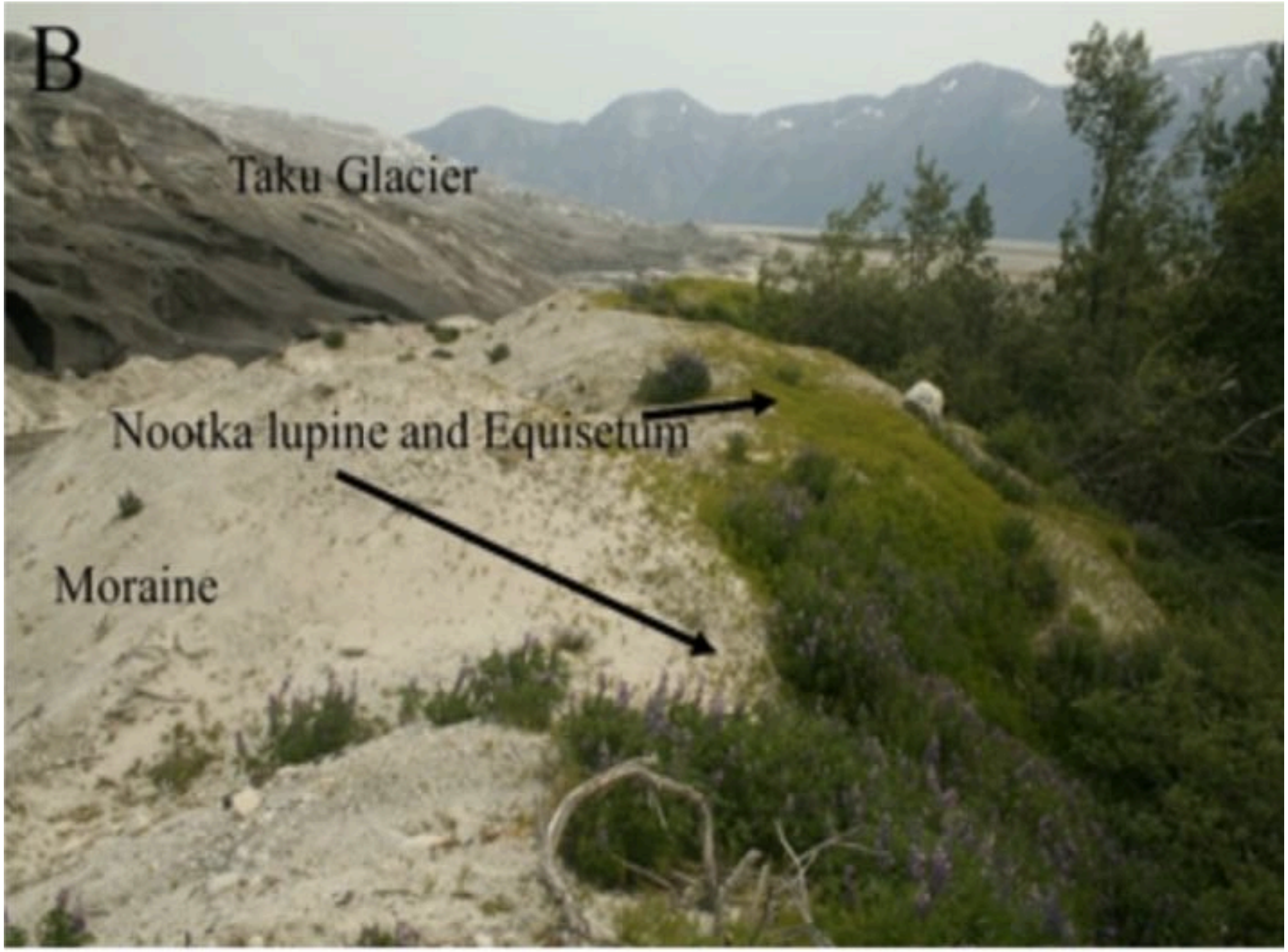
https://eos.org/science-updates/the-imminent-calving-retreat-of-taku-glacier

More evidence of retreat starting



Camera view

- The moraine is no longer being pushed and deformed.
- Vegetation is taking hold on the stationary moraine.



https://eos.org/science-updates/the-imminent-calving-retreat-of-taku-glacier

Tidewater glaciers and climate change

- Tidewater glaciers have an advance/retreat cycle that can take centuries.
- Retreat can be triggered by a small climate change, but once initiated, retreat is often inevitable.
    - severe ablation by warm water at the marine terminus.
- Once a tidewater glacier retreats back out of the water, a re-advance is often inevitable.
    - marine ablation is strongly reduced
    - Subaerial melting is reduced due to loss of ablation area
    - but accumulation upstream is still strong.

The tidewater cycle response

- can strongly amplify minor climate changes when the glacier is extended
- but is insensitive to climate changes at other points in the cycle.

Connection to global climate is weak

Glacier Bay

- Retreat began in 19^{th} C, but re-advance may be starting now.

Columbia Glacier

- Stable through the 19^{th} C, but retreat began late in 20^{th} C.
- Retreat may end soon.

Taku Glacier

- Advance began in mid 20^{th} C, but retreat may be starting now.

However, ongoing climate change may alter this, if the advance phase is interrupted by strong local warming.

- They might all just retreat in future.

Summary

- Non-surging glaciers that end on land respond most directly to climate (precipitation and melt on upper surface).
- Surge-type glaciers are relatively rare, except in Alaska-St Elias, Iceland, and Svalbard. Surges reflect changes in the subglacial hydrology conditions (sliding at lower surface).
- Tidewater glaciers advance and retreat in response to ablation and calving conditions (melting by seawater at the terminal front).

Questions for Curious Scientists

In the popular press, melting glaciers are now often viewed as "the smoking gun" for ongoing climate change caused by humans.
Due to its fame and accessibility, images of retreating Columbia Glacier are often used to illustrate that message.

- Discuss with your partners the potential risks (if any) and benefits (if any) of using Columbia Glacier in this context.

https://docs.google.com/document/d/1jHgUpCm2SAxpWXqfdgARPlM1HBKLv4J0Xo_dKGtbDnM/edit

Is the Antarctic Ice Sheet Doomed?

- Marine Ice Sheet Instability
- Marine Ice Cliff Instability

Nature 271, 321-325. (1978)

West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

J. H. Mercer

Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210

If the global consumption of fossil fuels continues to grow at its present rate, atmospheric CO_2 content will double in about 50 years. Climatic models suggest that the resultant greenhouse-warming effect will be greatly magnified in high latitudes. The computed temperature rise at lat 80° S could start rapid deglaciation of West Antarctica, leading to a 5 m rise in sea level.

ATMOSPHERIC carbon dioxide traps some of the long-wave radiation emitted by the Earth's surface (principally near 15 μm wavelength), thereby tending to warm the troposphere. This so-called greenhouse effect has long been suspected[1,2] but only recently, as the implications of a continuation of the current near-exponential growth of industrial CO_2 production have been realised, have many come to fear a disastrous climatic warming in the rather near future. In a recent report on the climatic effects of energy production, Revelle *et al.*[3] conclude that industrial civilisation may soon have to decide whether or not to make the tremendous investment of capital and effort needed to change over from fossil fuels to other sources of energy. Bolin[4], in hearings before the

If so, the actual doubling time for atmospheric CO_2 content is likely to be nearer 50 than 200 years.

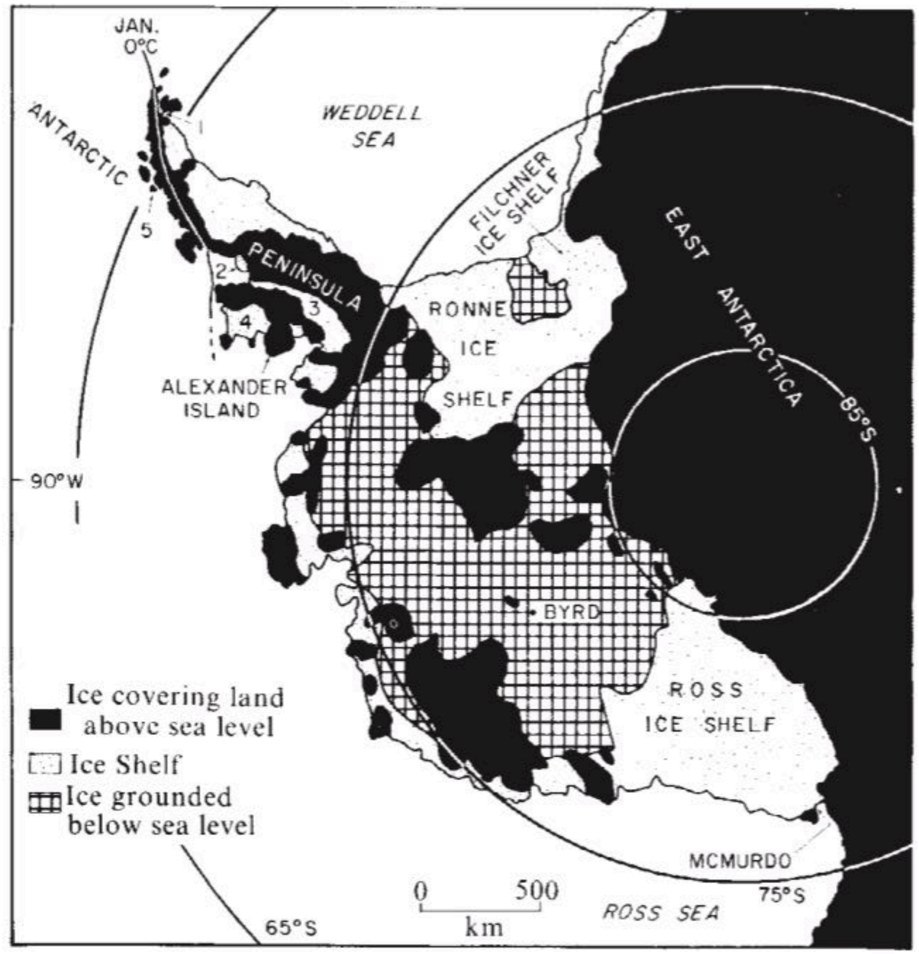
Many attempts have been made to estimate by climatic modelling the average global rise in temperature that would result from a doubling of atmosphere CO_2 content. The figures obtained have ranged from 0.7 K to 9.6 K, and Schneider[7] has critically examined the models in an attempt to clear up the confusion created by these widely different estimates. He points out that some of the models give unrealistic results because they compute an equilibrium condition for the Earth's surface rather than for the Earth–atmosphere system as a whole. He stresses the advantages of radiative–convective models, which take into account vertical motions of the atmosphere and latent heat transport, and he compares the radiative–convective models of Rasool and Schneider[8], who had computed an average global temperature rise of 0.8 K, with that of Manabe and Wetherald[9] who had computed a rise of 2.3 K, later revising this to 2.9 K. He estimates that, using the most refined input of feedback mechanisms that is possible with present knowledge, globally-averaged temperatures would rise about 1.9 K. But, because some feedback mechanisms may have been improperly modelled, some (especially those involving changes in cloud cover and cloud

Mercer (1978) *Nature*

In 1978, most climate models considered only surface melting as the process that would shrink the ice sheets in a warming green-house world. The process would take millennia.

- Mercer pointed out that the bed of the West Antarctic Ice Sheet (WAIS) is far below sea level.
- The WAIS could simply float if it got thin enough.
- If the buttressing ice shelves broke up, the thinning might happen fast.

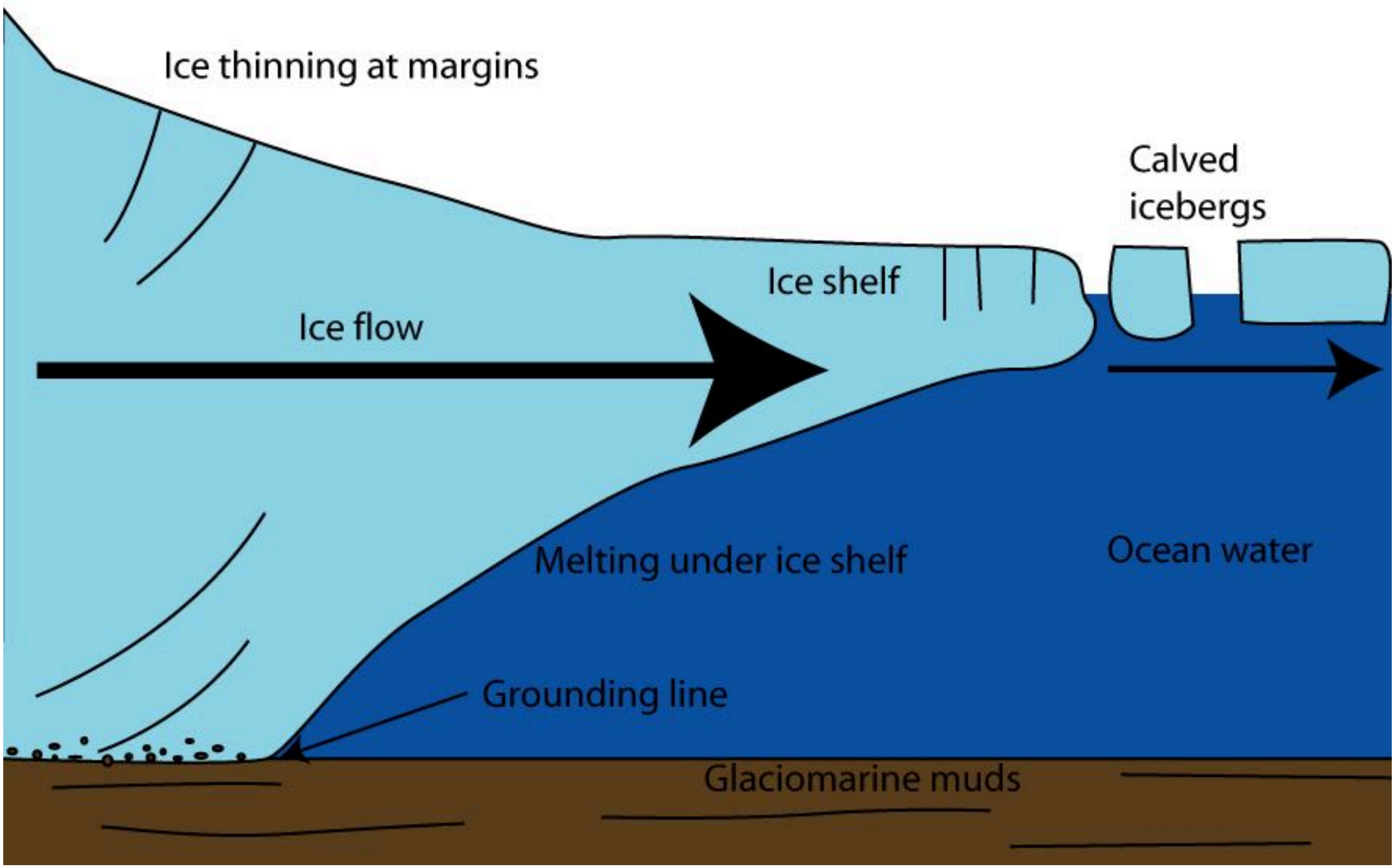
Ooops…!



Marine Ice Sheet, Ice Streams, and Ice Shelves

Vertical exaggeration
(~100x)

www.AntarcticGlaciers.org
Simplified schematic figure of a grounding line



T.J.Hughes (1981) – Weak underbelly letter to the editor *J .Glaciology*

SIR, *The weak underbelly of the West Antarctic ice sheet*

Possible collapse of the West Antarctic ice sheet by surges of Thwaites and Pine Island Glaciers into the Pine Island Bay polynya of the Amundsen Sea was a subject addressed in papers by Lingle and Clark (1979) and Thomas (1979), and in abstracts by Denton and others (1979) and Hughes (1979), that were published in Vol. 24, No. 90 of the *Journal of Glaciology*. This concept was first developed in 1975 by George H. Denton and me as part of our CLIMAP responsibilities to reconstruct the maximum Antarctic ice sheet and then to disintegrate the marine West Antarctic portion. Lingle and Clark (1979) have acknowledged us and CLIMAP in this regard, and we are grateful to them.

A brief history of the development of the concept that Pine Island Bay may be the weak underbelly of the West Antarctic ice sheet is in order, because the American Society for the Advancement of Science (AAAS) and the United States Department of Energy (DOE) sponsored a workshop at the University of Maine on 8–10 April 1980 to formulate a science plan that would "elucidate the research that might establish once and for all the likelihood and time frame of collapse of the grounded ice" in West Antarctica (David M. Burns, Director of the AAAS/DOE Climate Project, letter of 11 October 1979).

CLIMAP (Climate: Long-range Investigations, Mapping, and Prediction) conducted two experiments, reconstructing the maximum ice-age climate 18 000 years ago and the maximum interglaciation climate 125 000 years ago. George H. Denton was the Principal Investigator responsible for providing the areas, elevations, and volumes of ice sheets as input boundary conditions for these two CLIMAP experiments. This work was done at the University of Maine, where I was the Task Group Leader responsible for numerically reconstructing and disintegrating ice sheets having areal extents specified by Denton. Results of this work are presented in chapter 6 (Hughes and others, 1981) and chapter 7 (Stuiver and others, 1981) of *The last great ice sheets*.

Hughes, T. (1981), The weak underbelly of the West Antarctic ice sheet, *J. Glaciol.*, *27*(97), 518–525

Hughes – Weak underbelly letter (1981)

Possible collapse of the West Antarctic Ice Sheet by surges of Thwaites and Pine Island Glaciers …

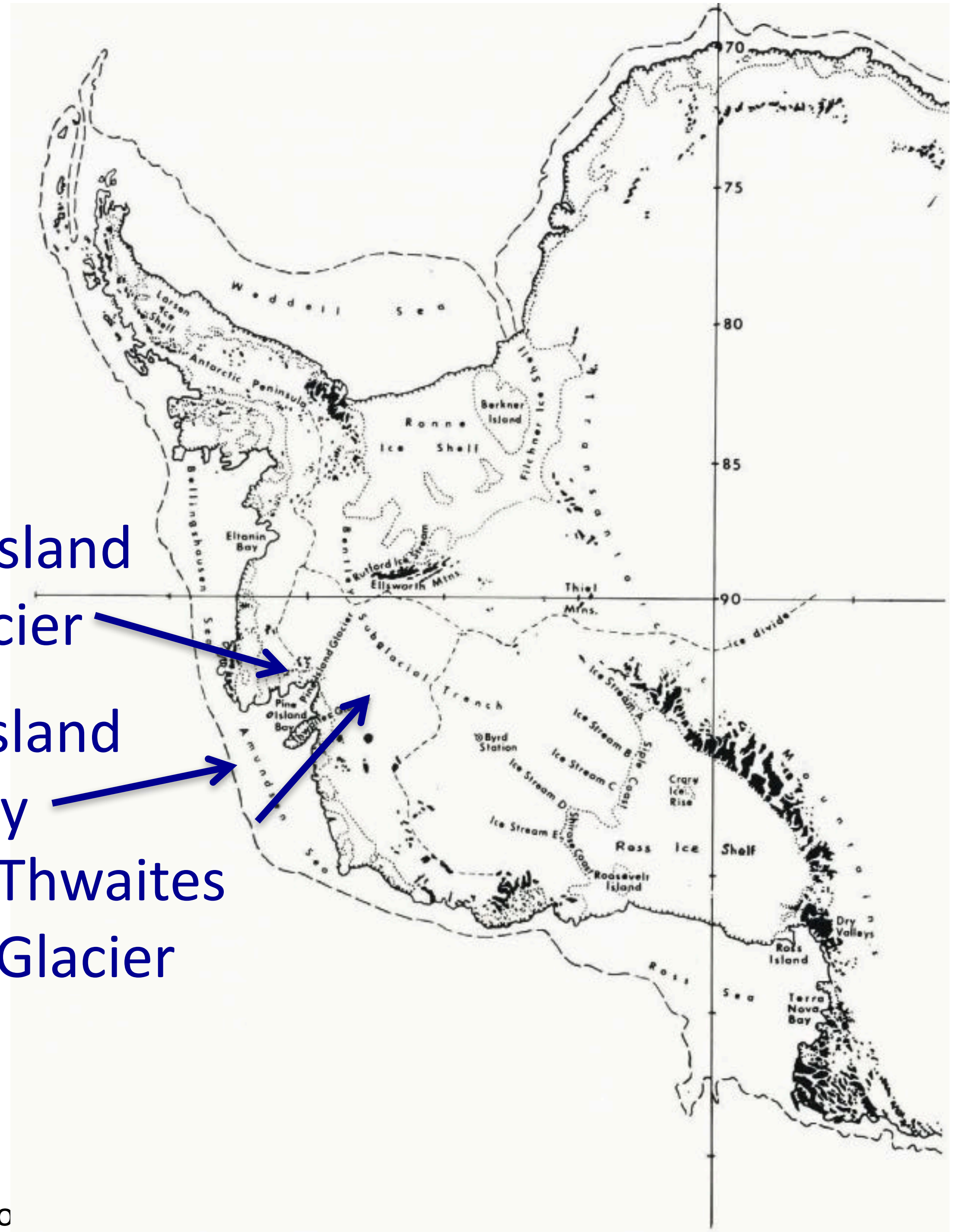
A brief history of the development of the concept that Pine Island Bay may be the weak underbelly of the West Antarctic ice sheet is in order. … AAAS *[publishers of Science]* and *DOE [US Dept of Energy]* … sponsored a workshop … in April 1980 … to formulate a science plan that would ”elucidate the research that might establish once and for all the likelihood and time frame of collapse of the grounded ice in West Antarctica”.

2021 – we are still working on that …

Hughes, T. (1981), The weak underbelly of the West Antarctic ice sheet, *J. Glaciol.*, *27*(97), 518–525

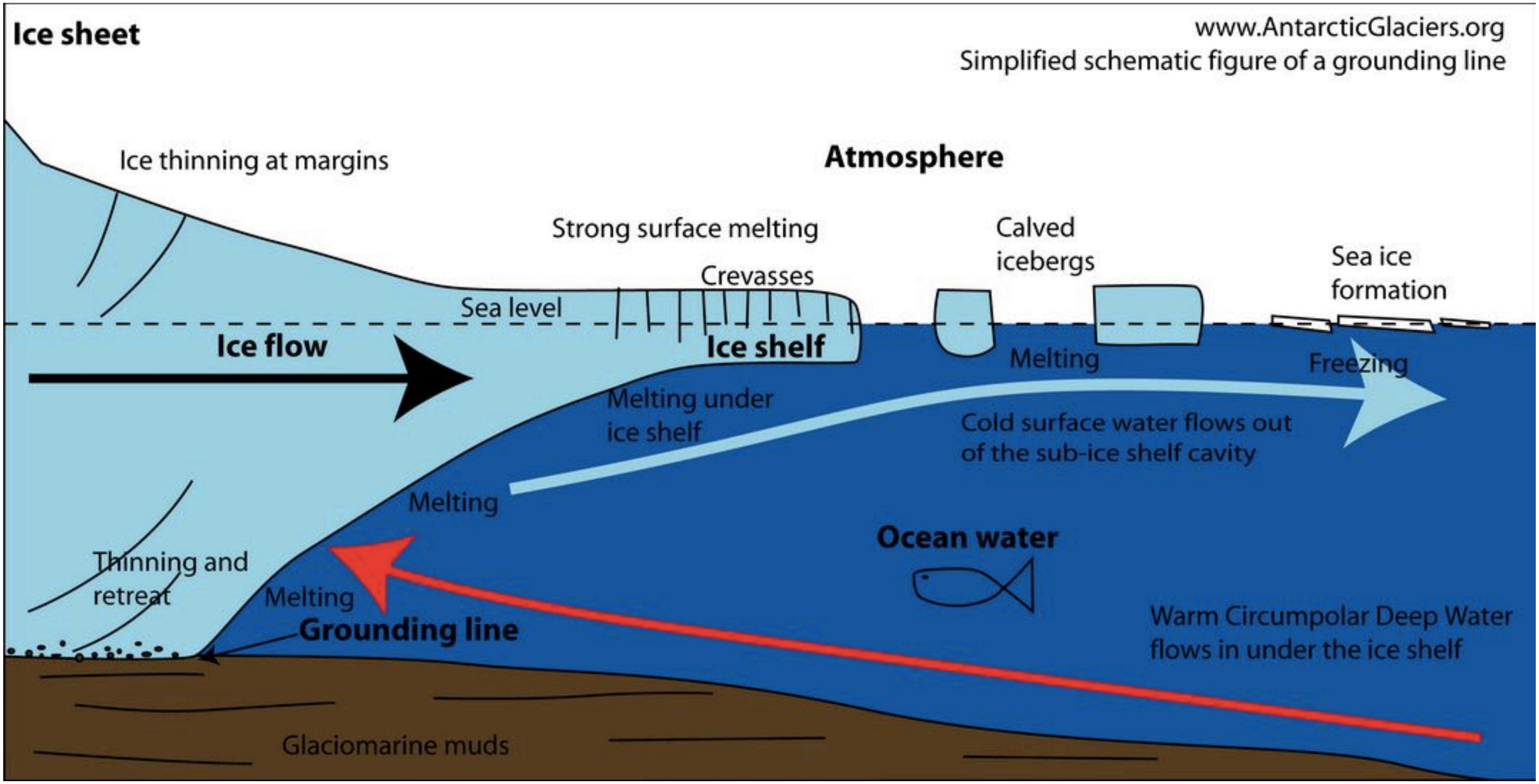
Hughes –
Weak underbelly
letter (1981)

(1981 graphics)



Hughes, T. (1981), The weak underbelly o

Ice Shelf Processes



Is there really a problem?

- How thick is the ice everywhere in Antarctica?
- Can the bed really be below sea level when the surface is at 2 km?

- BEDMAP 2 - Fretwell et al. (2013) *The Cryosphere*

BEDMAP 2 - Data sets for Antarctica

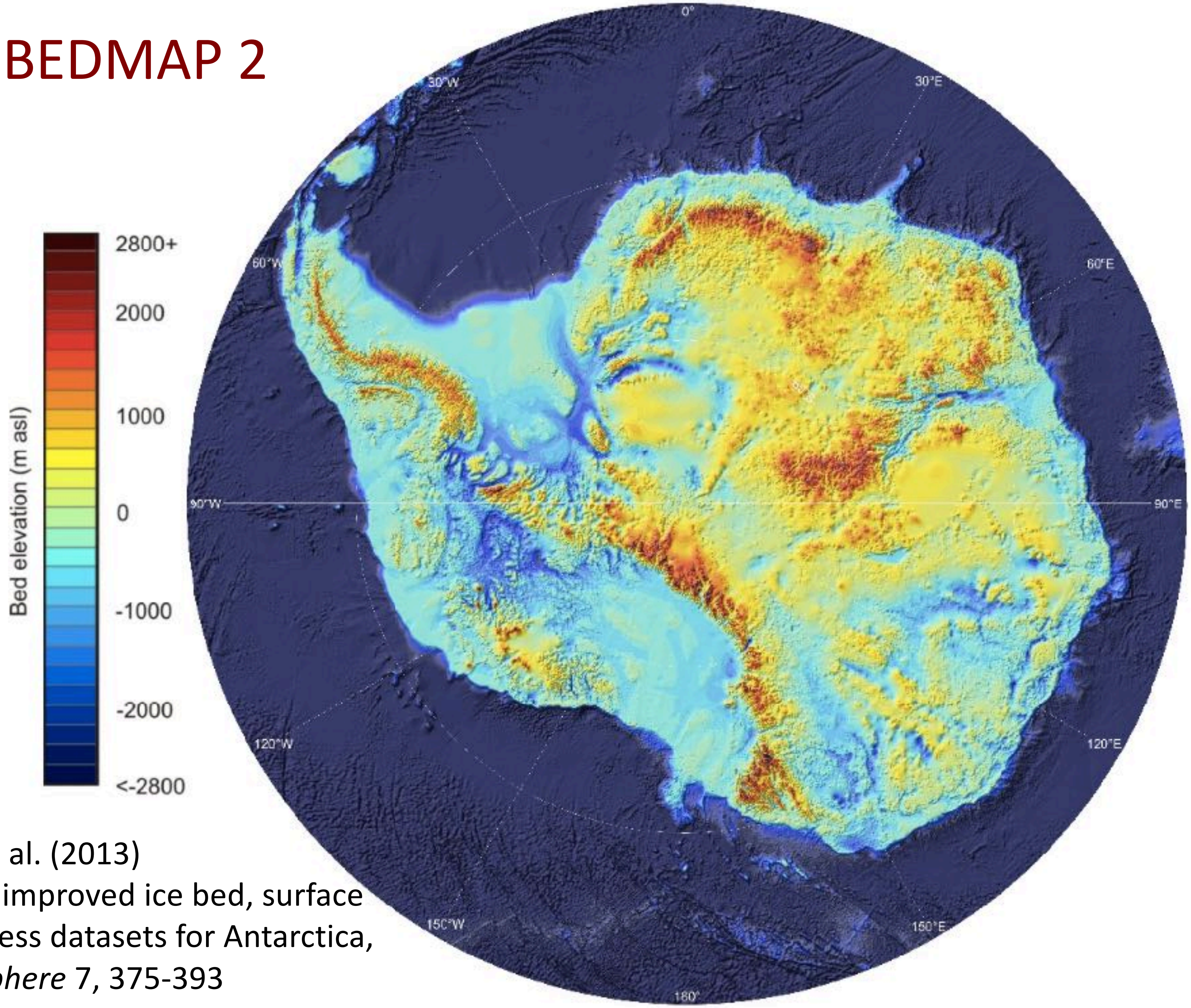
The Cryosphere, 7, 375–393, 2013
www.the-cryosphere.net/7/375/2013/
doi:10.5194/tc-7-375-2013

The Cryosphere
Open Access

Bedmap2: improved ice bed, surface and thickness datasets for Antarctica

P. Fretwell[1,*], H. D. Pritchard[1,*], D. G. Vaughan[1], J. L. Bamber[2], N. E. Barrand[1], R. Bell[3], C. Bianchi[4], R. G. Bingham[5], D. D. Blankenship[6], G. Casassa[7], G. Catania[6], D. Callens[8], H. Conway[9], A. J. Cook[10], H. F. J. Corr[1], D. Damaske[11], V. Damm[11], F. Ferraccioli[1], R. Forsberg[12], S. Fujita[13], Y. Gim[14], P. Gogineni[15], J. A. Griggs[2], R. C. A. Hindmarsh[1], P. Holmlund[16], J. W. Holt[6], R. W. Jacobel[17], A. Jenkins[1], W. Jokat[18], T. Jordan[1], E. C. King[1], J. Kohler[19], W. Krabill[20], M. Riger-Kusk[21], K. A. Langley[22], G. Leitchenkov[23], C. Leuschen[15], B. P. Luyendyk[24], K. Matsuoka[25], J. Mouginot[26], F. O. Nitsche[3], Y. Nogi[27], O. A. Nost[25], S. V. Popov[28], E. Rignot[29], D. M. Rippin[30], A. Rivera[7], J. Roberts[31], N. Ross[32], M. J. Siegert[2], A. M. Smith[1], D. Steinhage[18], M. Studinger[33], B. Sun[34], B. K.Tinto[3], B. C. Welch[18], D. Wilson[35], D. A. Young[6], C. Xiangbin[34], and A. Zirizzotti[4]

BEDMAP 2

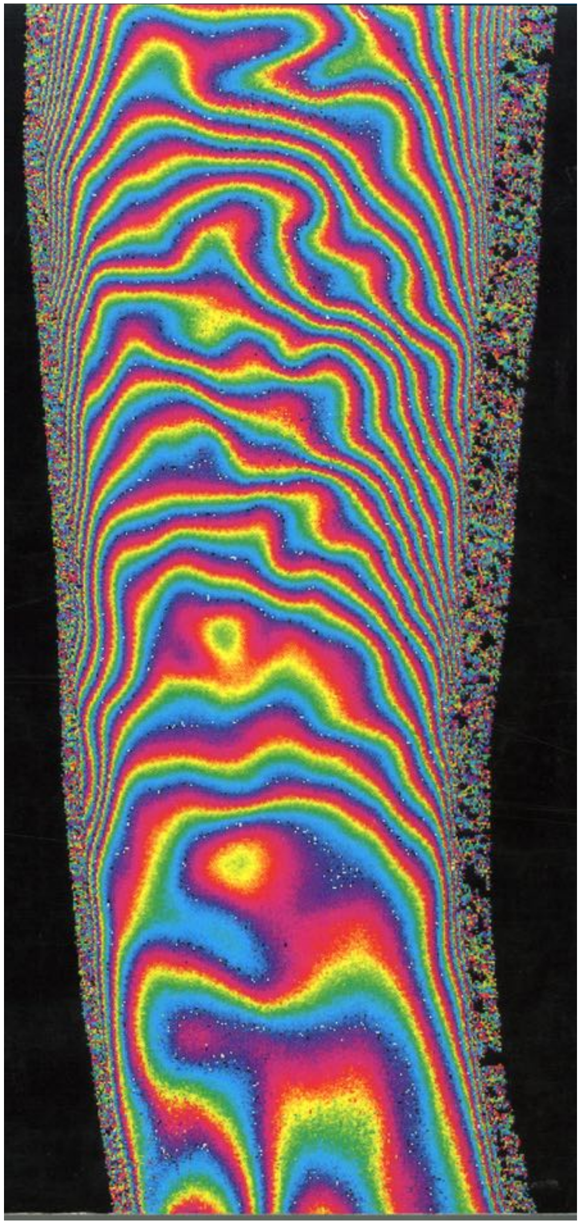


Fretwell et al. (2013)
Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, *The Cryosphere* 7, 375-393

How fast is the ice actually moving?

Satellites measure flow speed with radar interferograms.

- Compare two radar images of the same scene, taken with separation in time.
- Interference pattern produces color fringes.
- Each successive fringe indicates another half-wavelength difference in surface displacement in the time between images.
- It's like color fringes in an oil slick on water that record variations in its thickness.

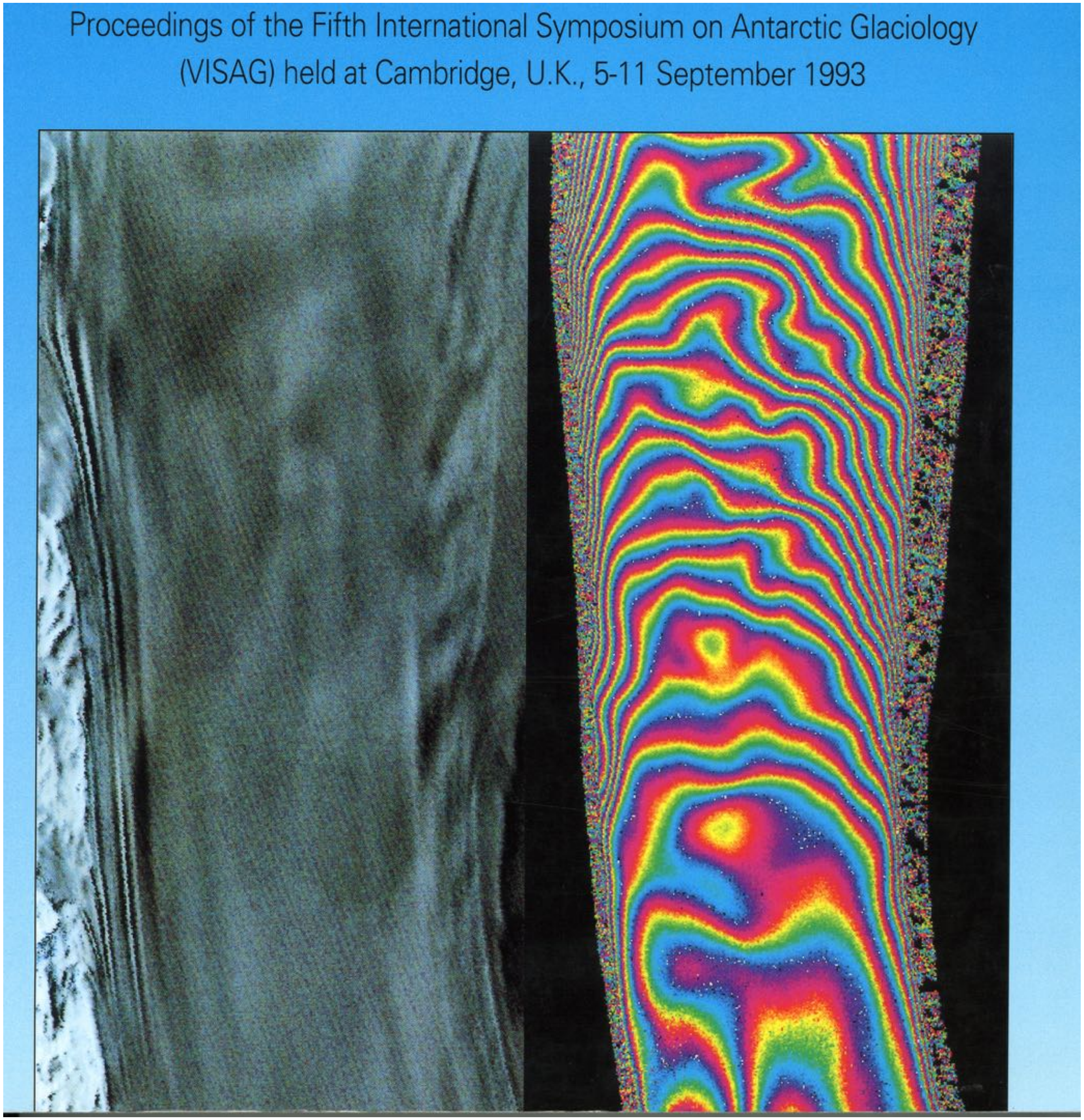


inSAR

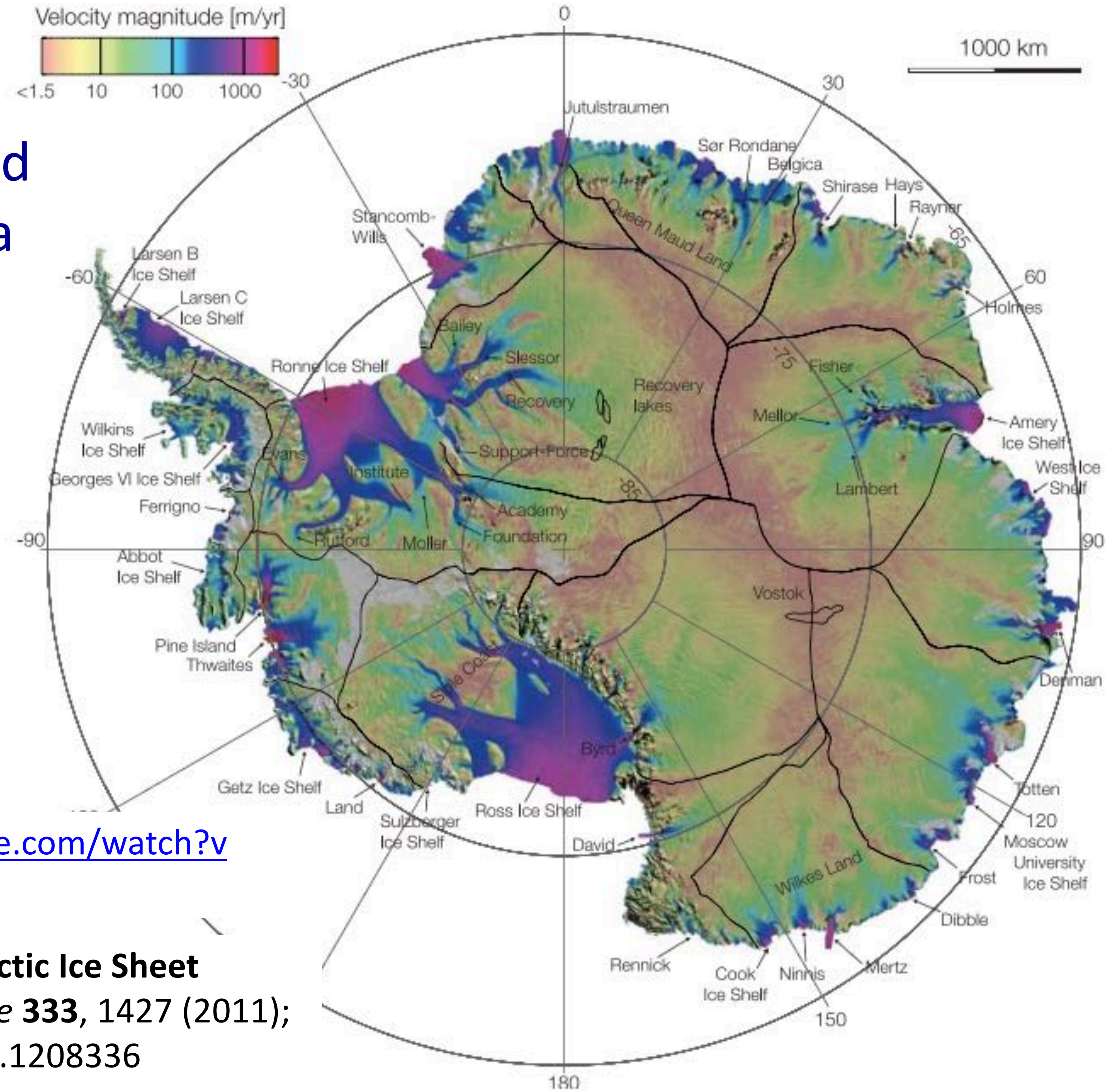
interferometric Synthetic Aperture Radar

To get speed, count fringes from a stationary point on bedrock.

Rutford Ice Stream, West Antarctica, flows toward the bottom of the image.



Surface speed in Antarctica



https://www.youtube.com/watch?v=KlDO0C8r_ws

Ice Flow of the Antarctic Ice Sheet
E. Rignot *et al. Science* **333**, 1427 (2011);
DOI: 10.1126/science.1208336

Ice flux into the sea can now be calculated from ice thickness and flow speed.

- Asking how long it would take to drain a glacier catchment is now possible …