Breaking with tradition: Dealing with unavoidable but imperfectly observed physics in ice-sheet models and sea-level rise

R.B. Alley

Nov. 28, 2018

The Future of Earth System Modeling: Polar Climates. Caltech

Please note: I work for Penn State University, and help UN IPCC, NRC, etc., But I am not representing them, just me.

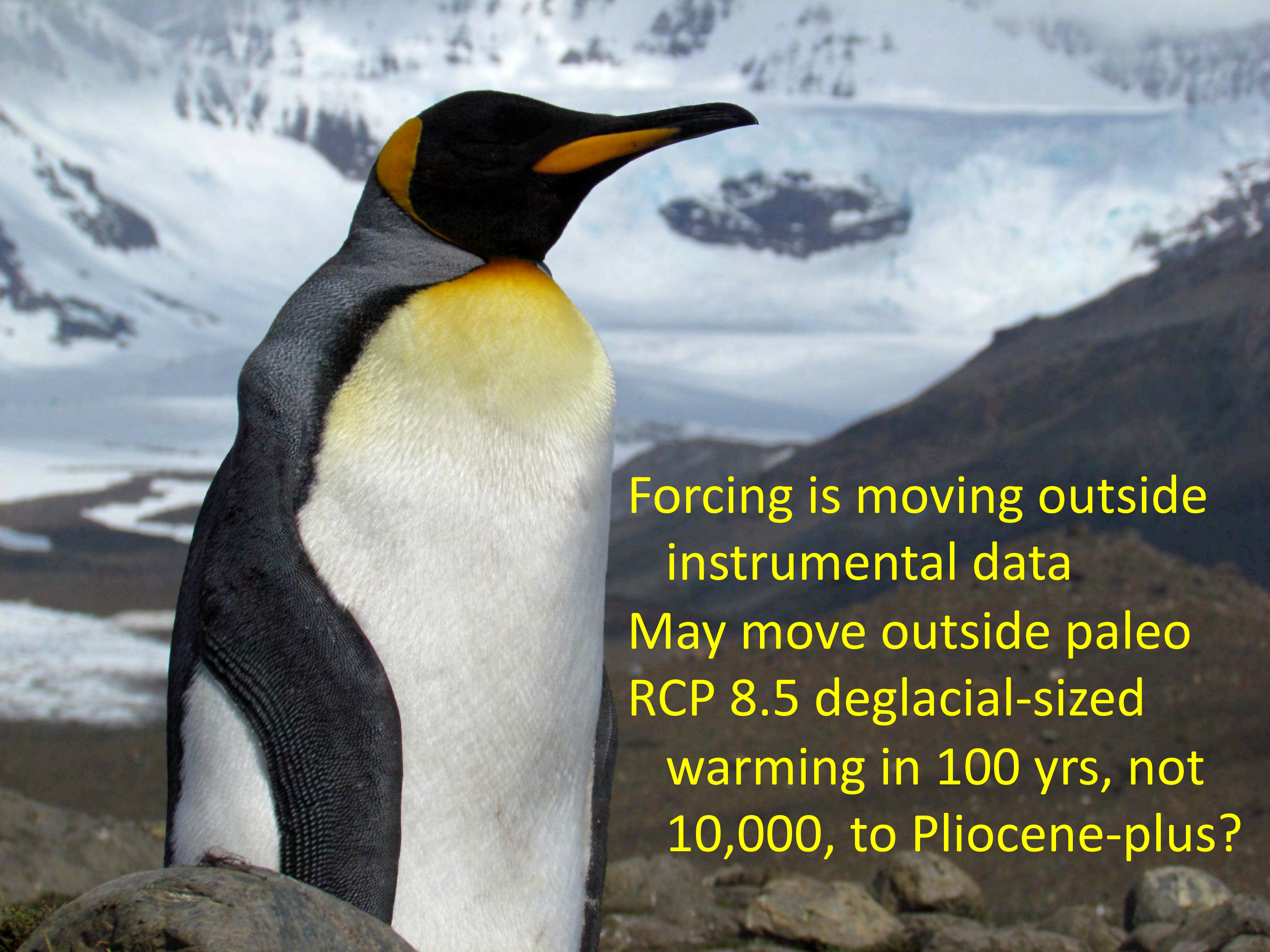
G. Comer Foundation

CRESIS

PENNSTATE

NASA

earth THE OPERATORS' MANUAL


Forcing is moving outside instrumental data
May move outside paleo
RCP 8.5 deglacial-sized warming in 100 yrs, not 10,000, to Pliocene-plus?

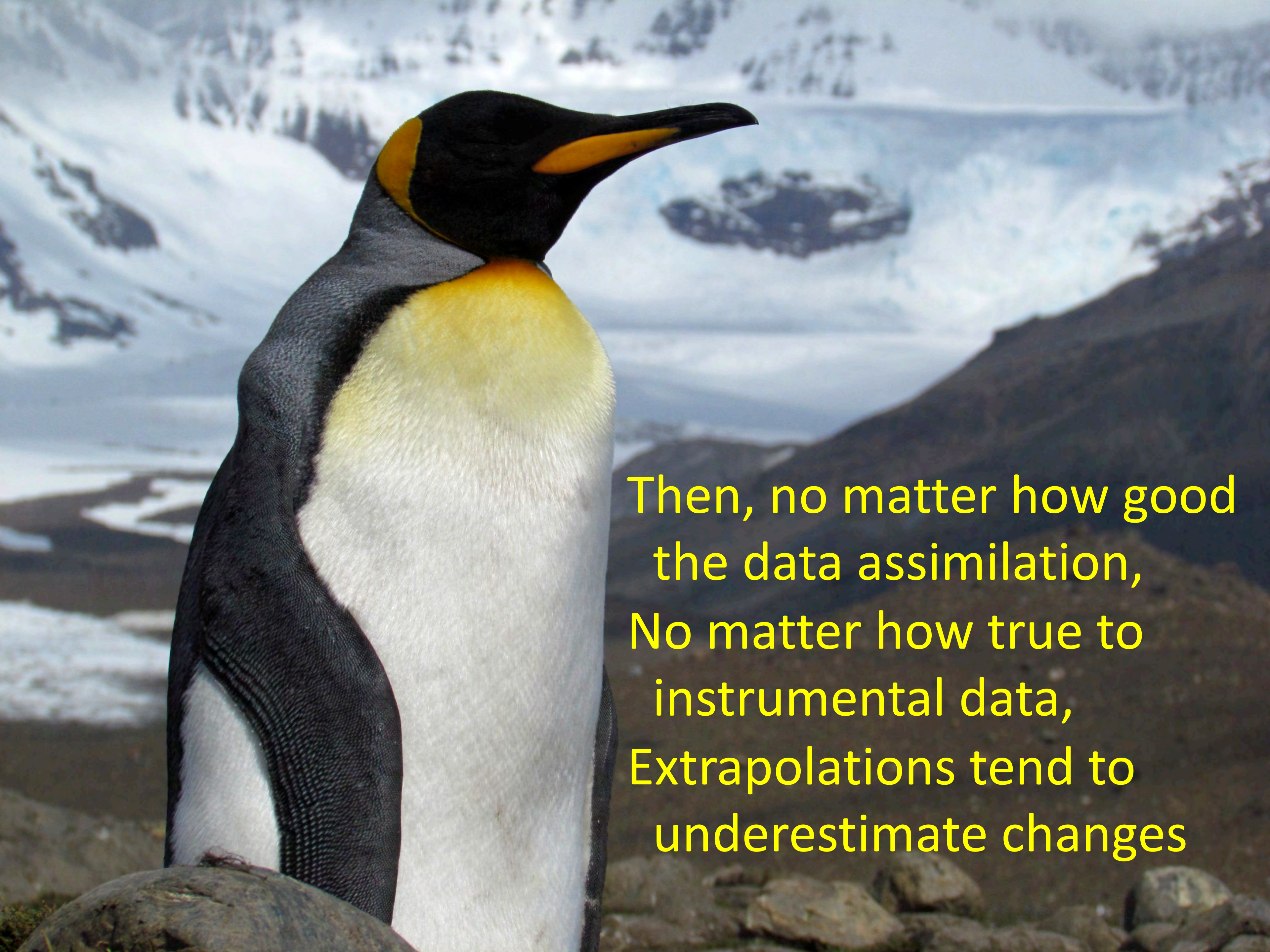

Then, no matter how good the data assimilation,
No matter how true to instrumental data,
Extrapolations tend to underestimate changes

Fig. 1, Shoji, H. & A. Higashi, 1978, A deformation mechanism map of ice, J.Glac. 21(85), 419-427

Deformation maps

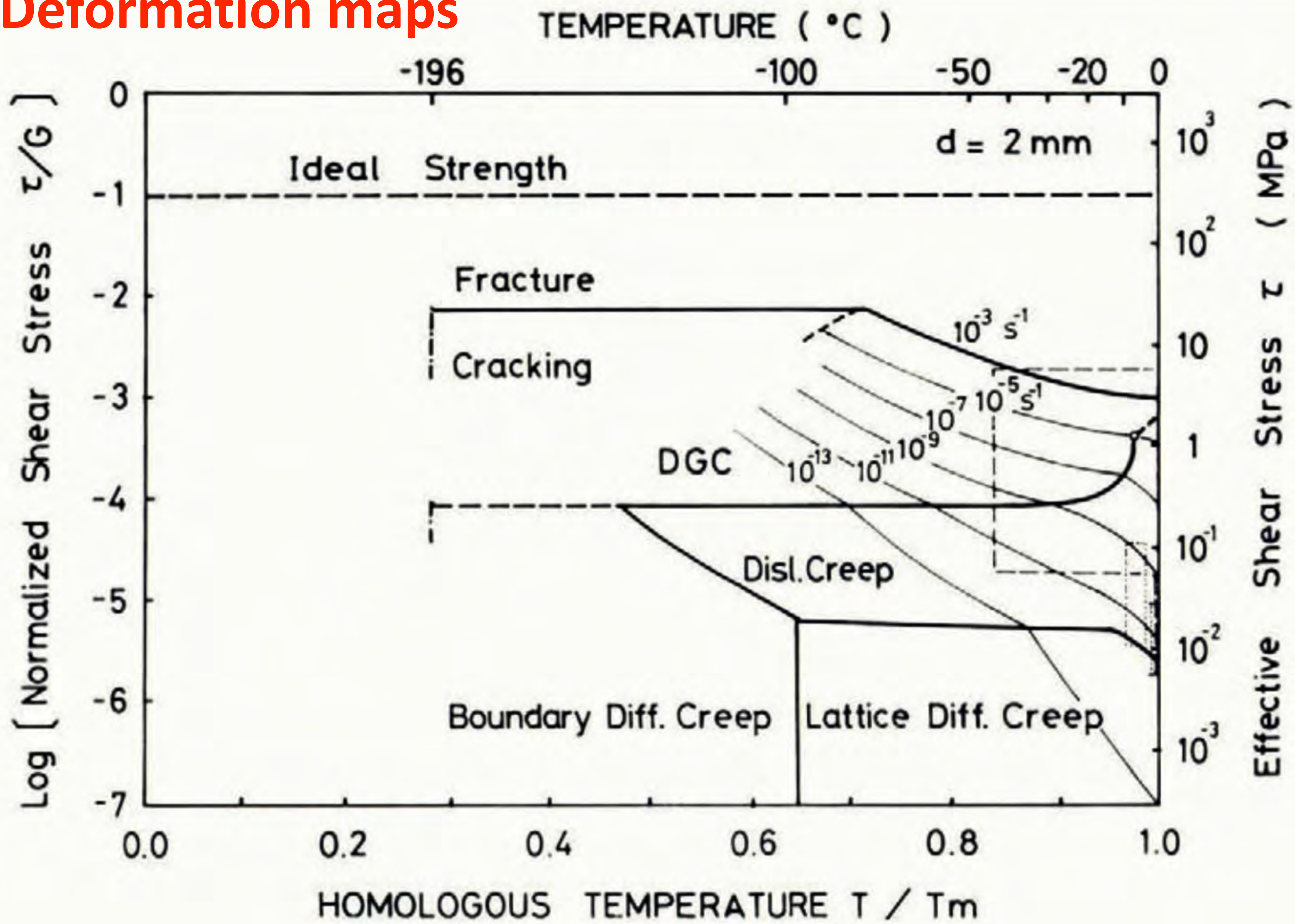


Fig. 1, Shoji, H. & A. Higashi, 1978, A deformation mechanism map of ice, J.Glac. 21(85), 419-427

Deformation maps

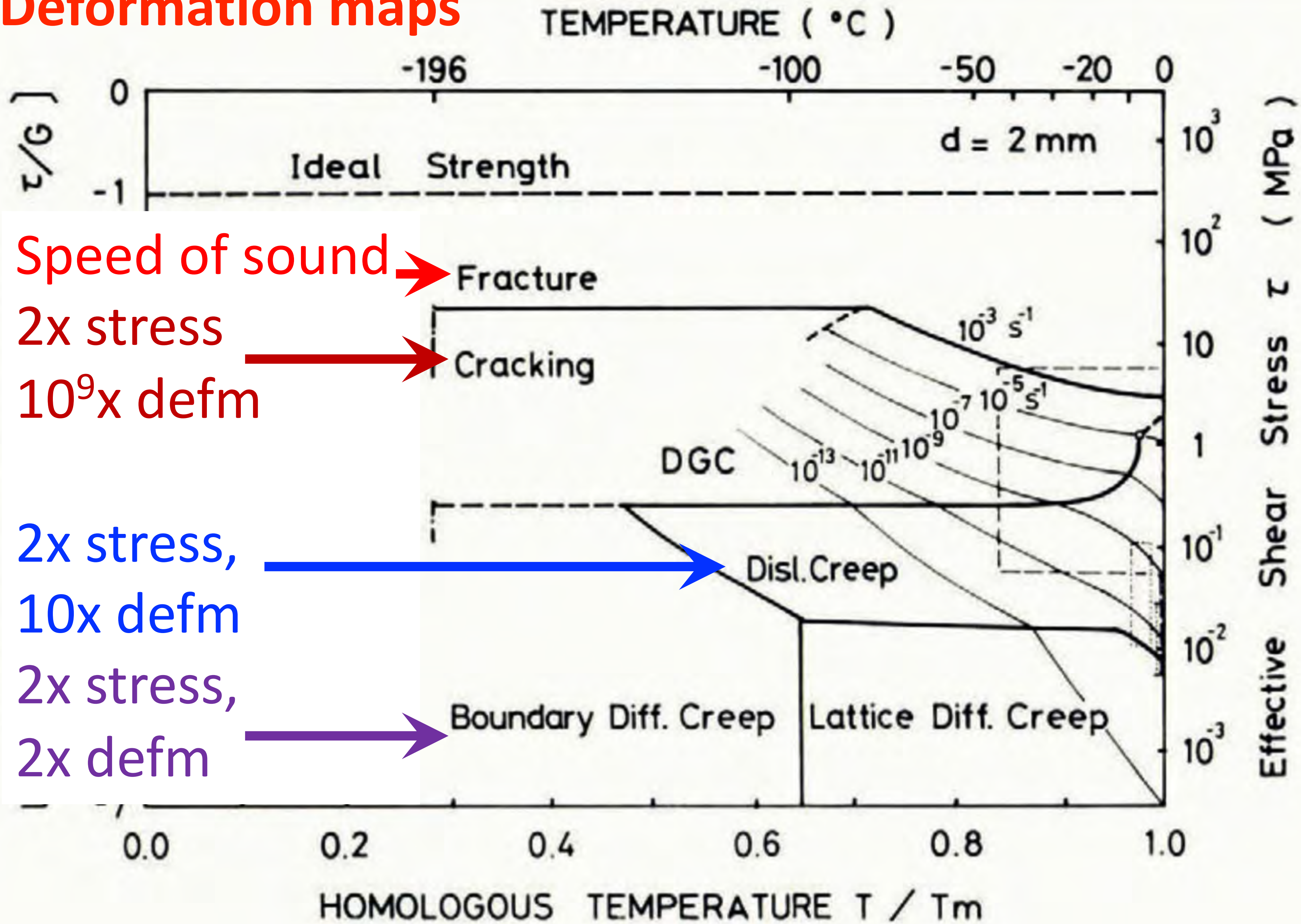
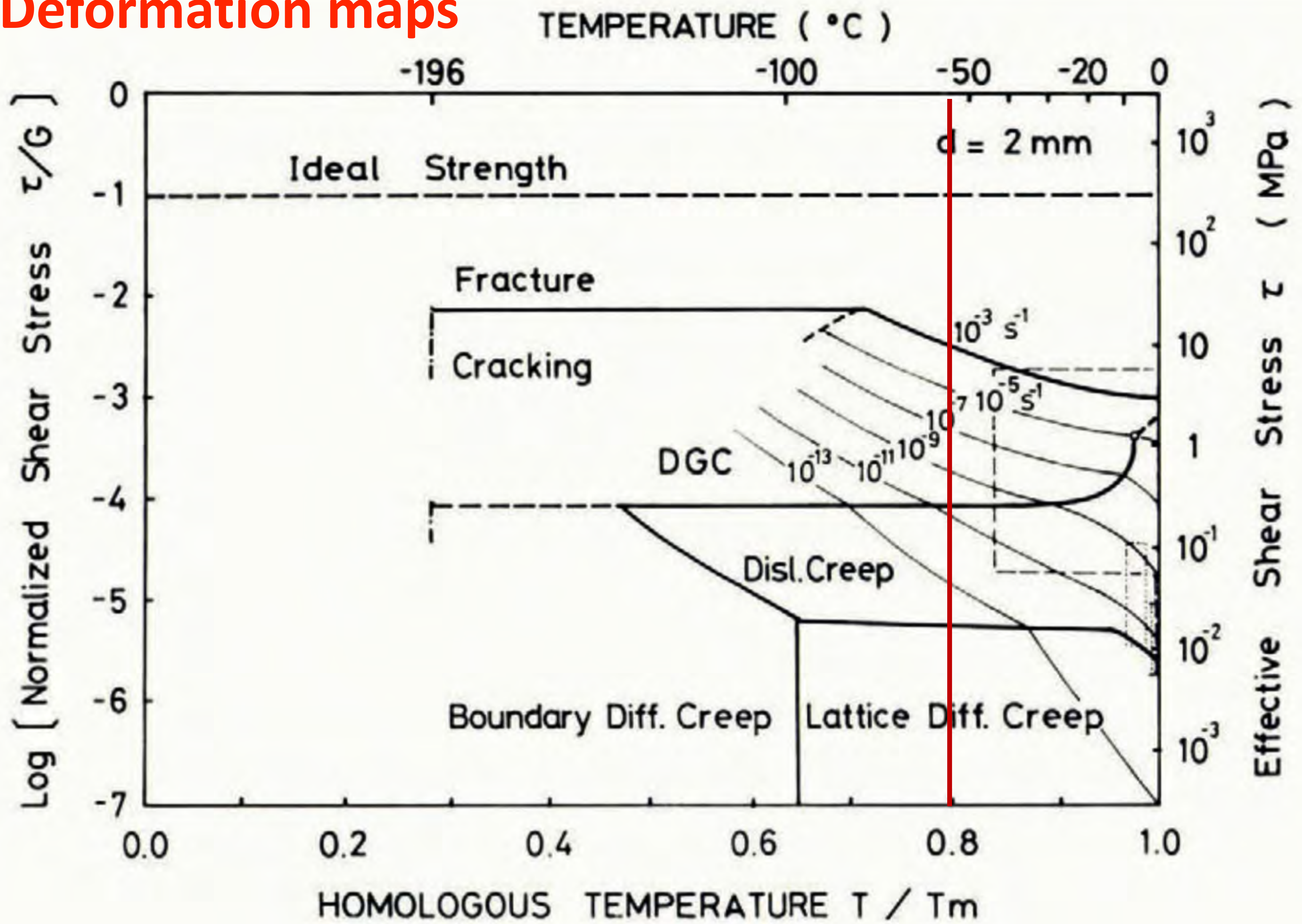


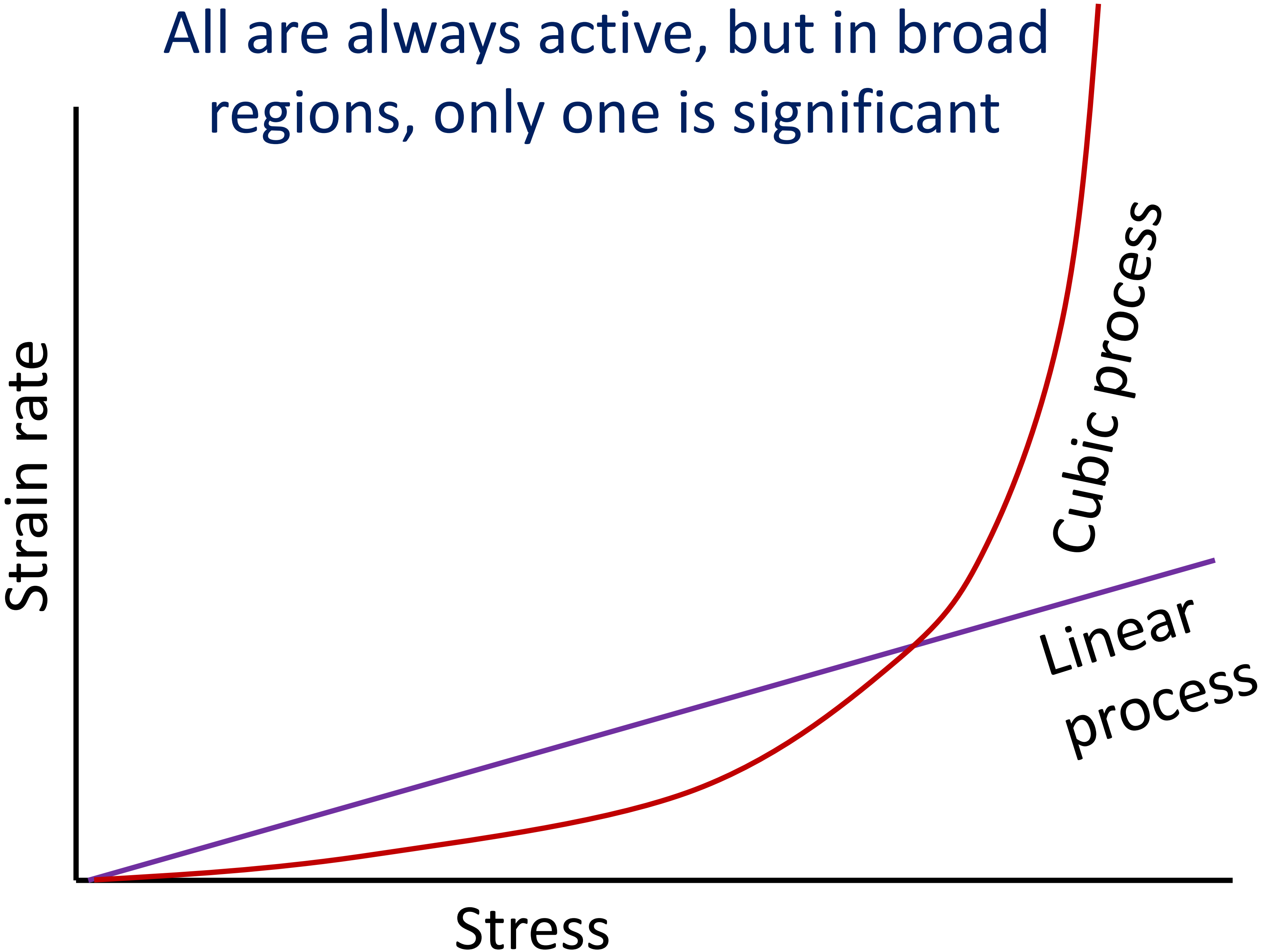
Fig. 1, Shoji, H. & A. Higashi, 1978, A deformation mechanism map of ice, J.Glac. 21(85), 419-427

Deformation maps



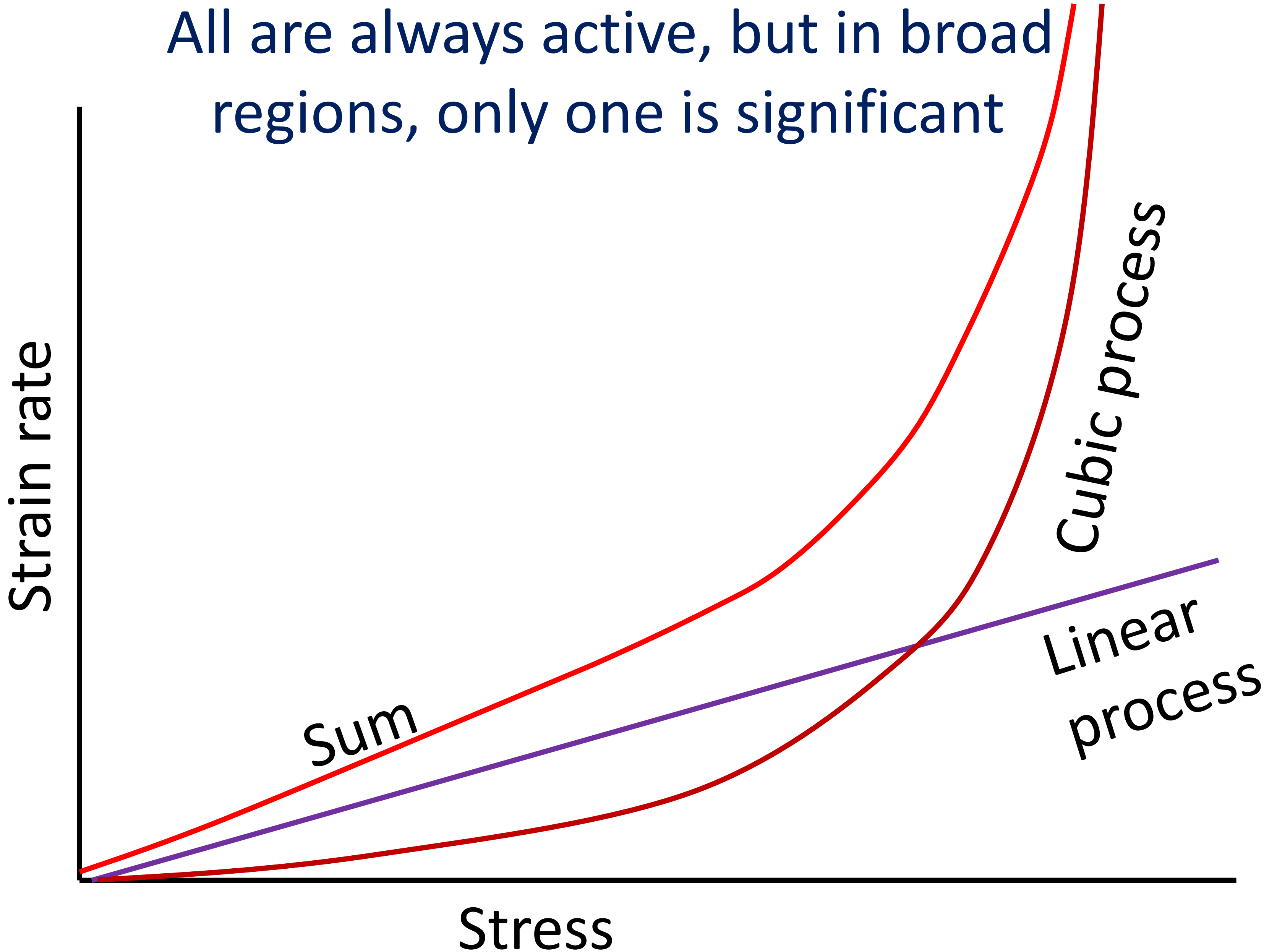
Cartoon of deformation mechanisms

All are always active, but in broad regions, only one is significant

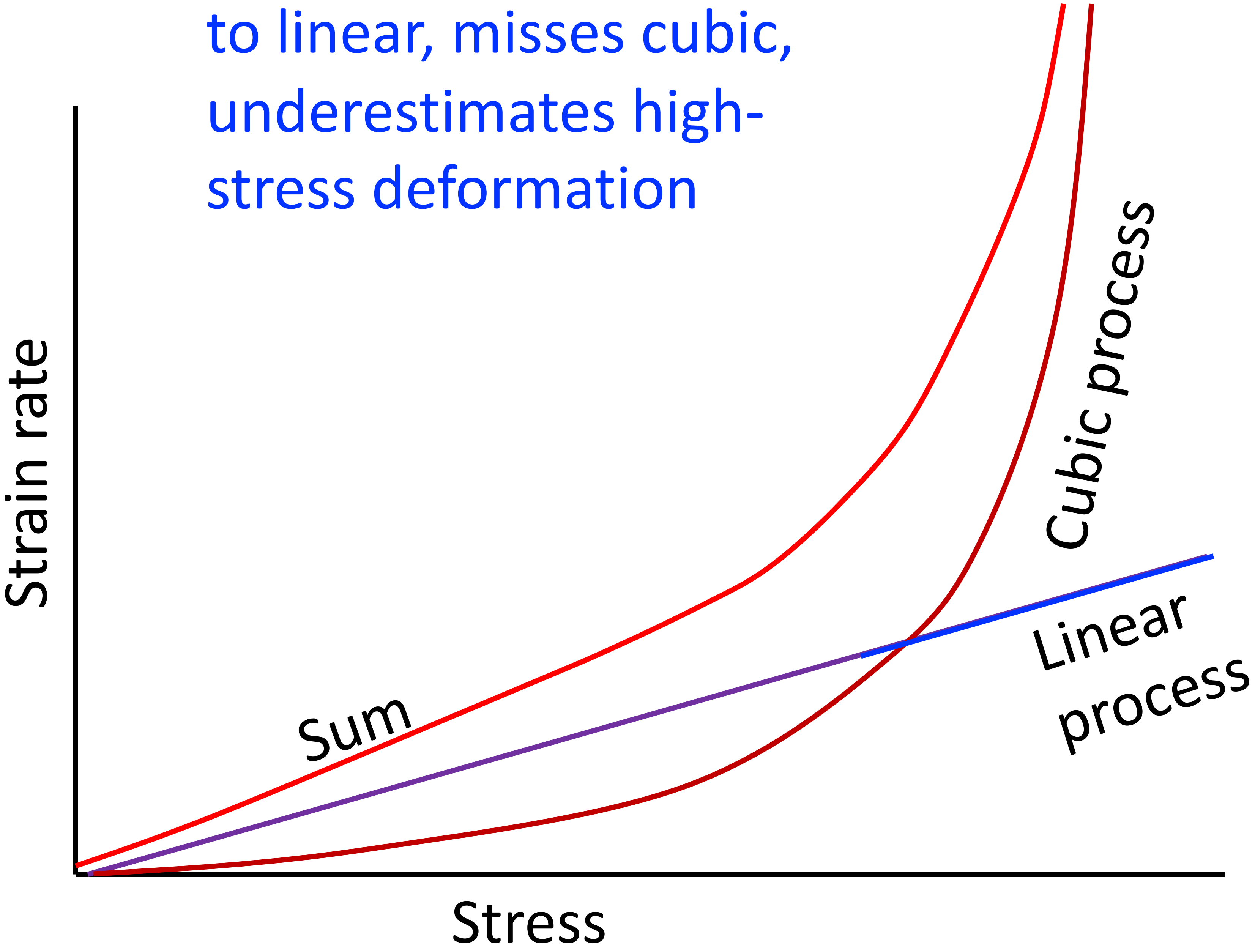


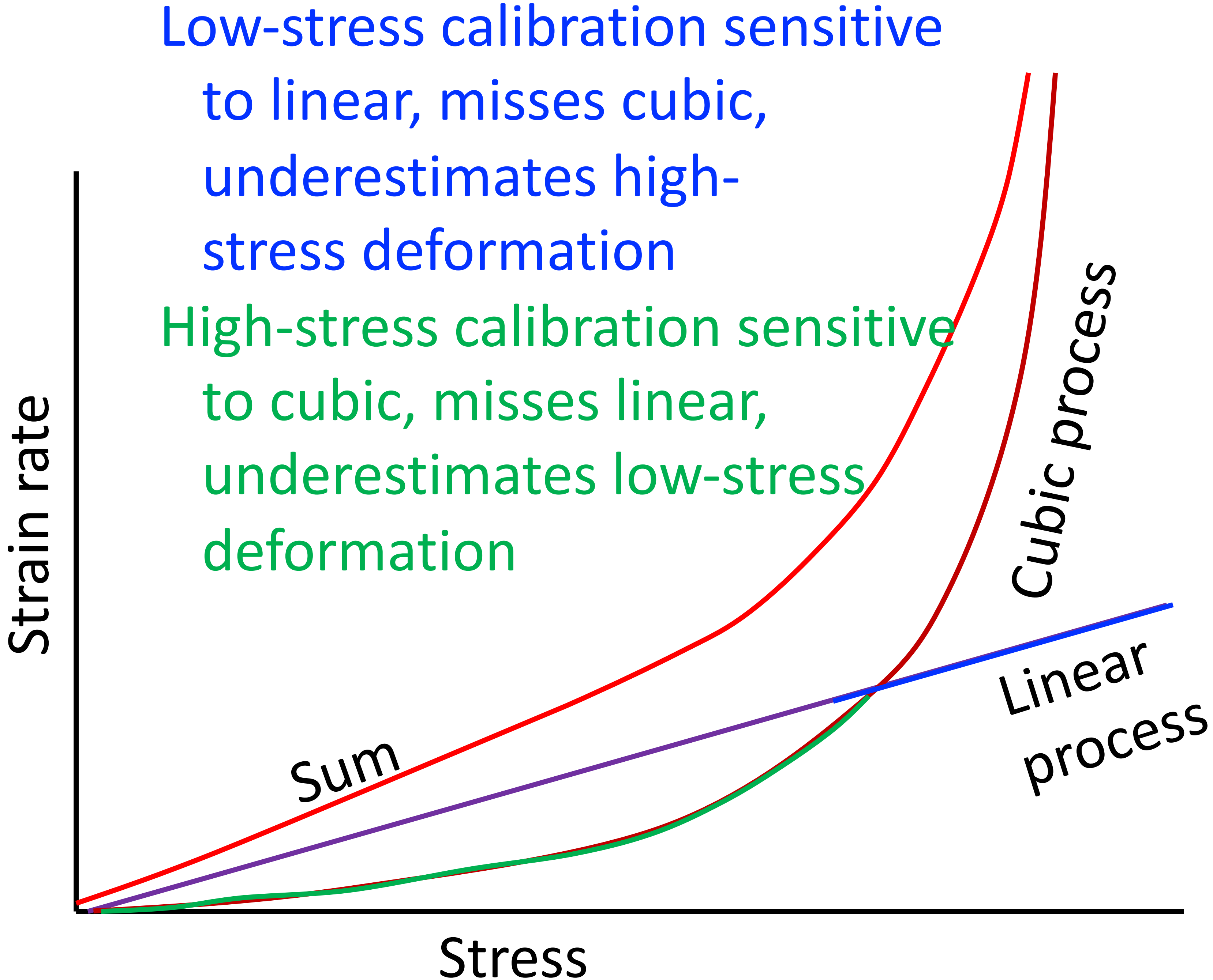
Cartoon of deformation mechanisms

All are always active, but in broad regions, only one is significant



Low-stress calibration sensitive to linear, misses cubic, underestimates high-stress deformation




Low-stress calibration sensitive to linear, misses cubic, underestimates high-stress deformation
High-stress calibration sensitive to cubic, misses linear, underestimates low-stress deformation
Strain rate
Stress
Sum
Cubic process
Linear process

→Many deformation mechanisms

→Rates~$A_o \exp[-Q/(RT)]\tau^n$

→n=1 (several processes) to ~30 (subcritical crack growth), wide range of Q

→For some (T, τ) one process dominates

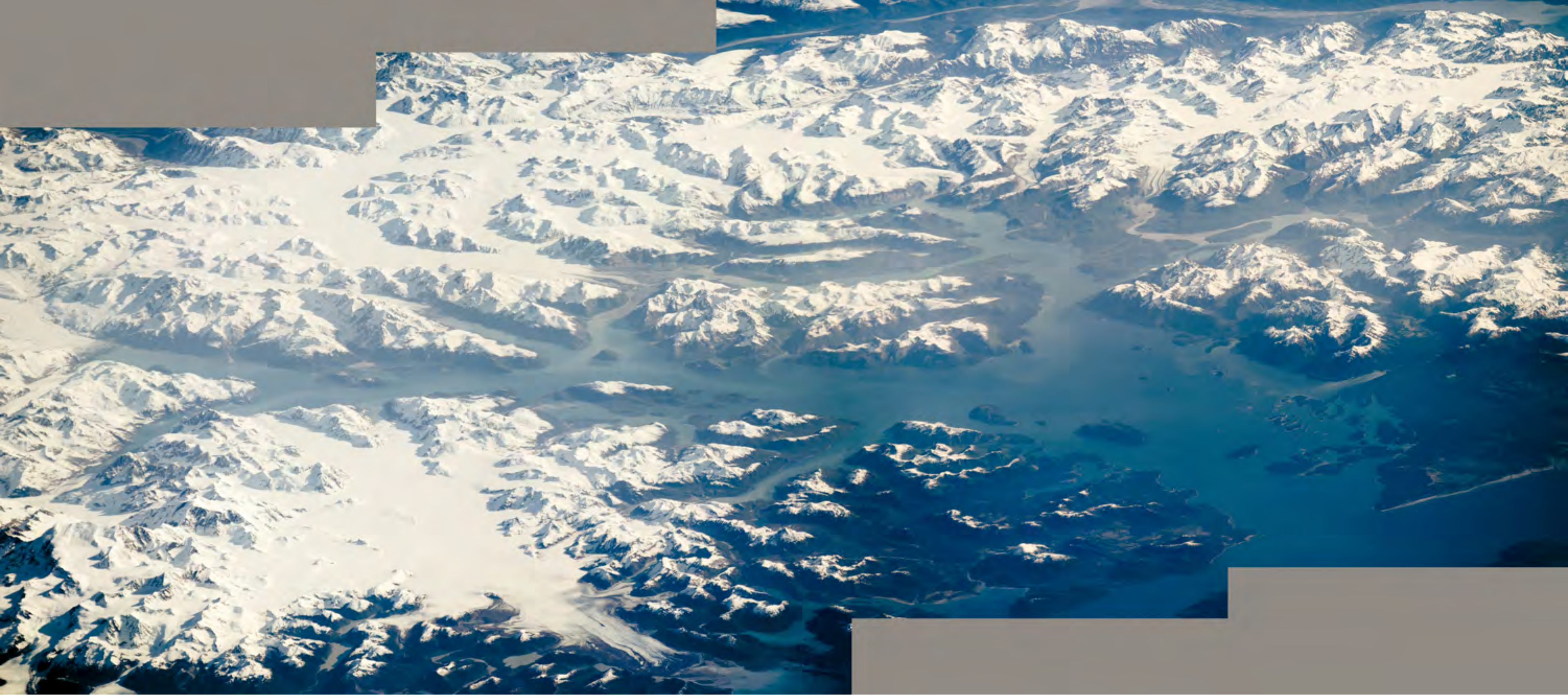
→Data are sensitive to only that process

→If extrapolated too far, some other process always grows to dominate

→And model always underestimates rate

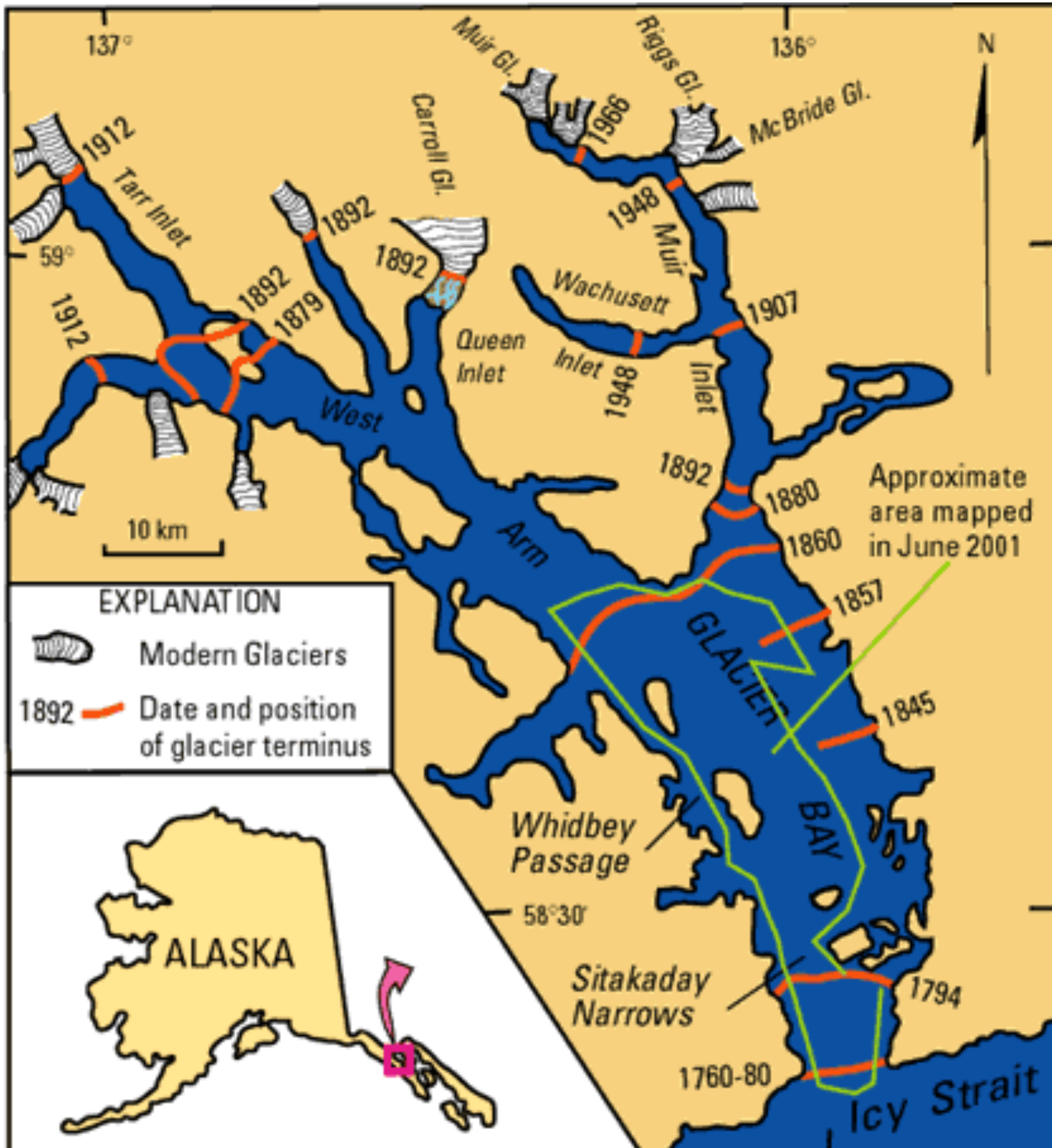
→Extrapolations underestimate rate
→Very clear for ice deformation
→Especially at onset of fracture
→Probably for basal sliding as well
→I’m happy to discuss (Iken limit, till deformation viscous-plastic, role of ice deformation in sliding; R-channels unclear but likely don’t change answer)


If you want buildings, bridges and ice sheets to persist, then rule is:
All extrapolations are overly optimistic



https://earthobservatory.nasa.gov/images/88701/glacier-bay-national-park-preserve

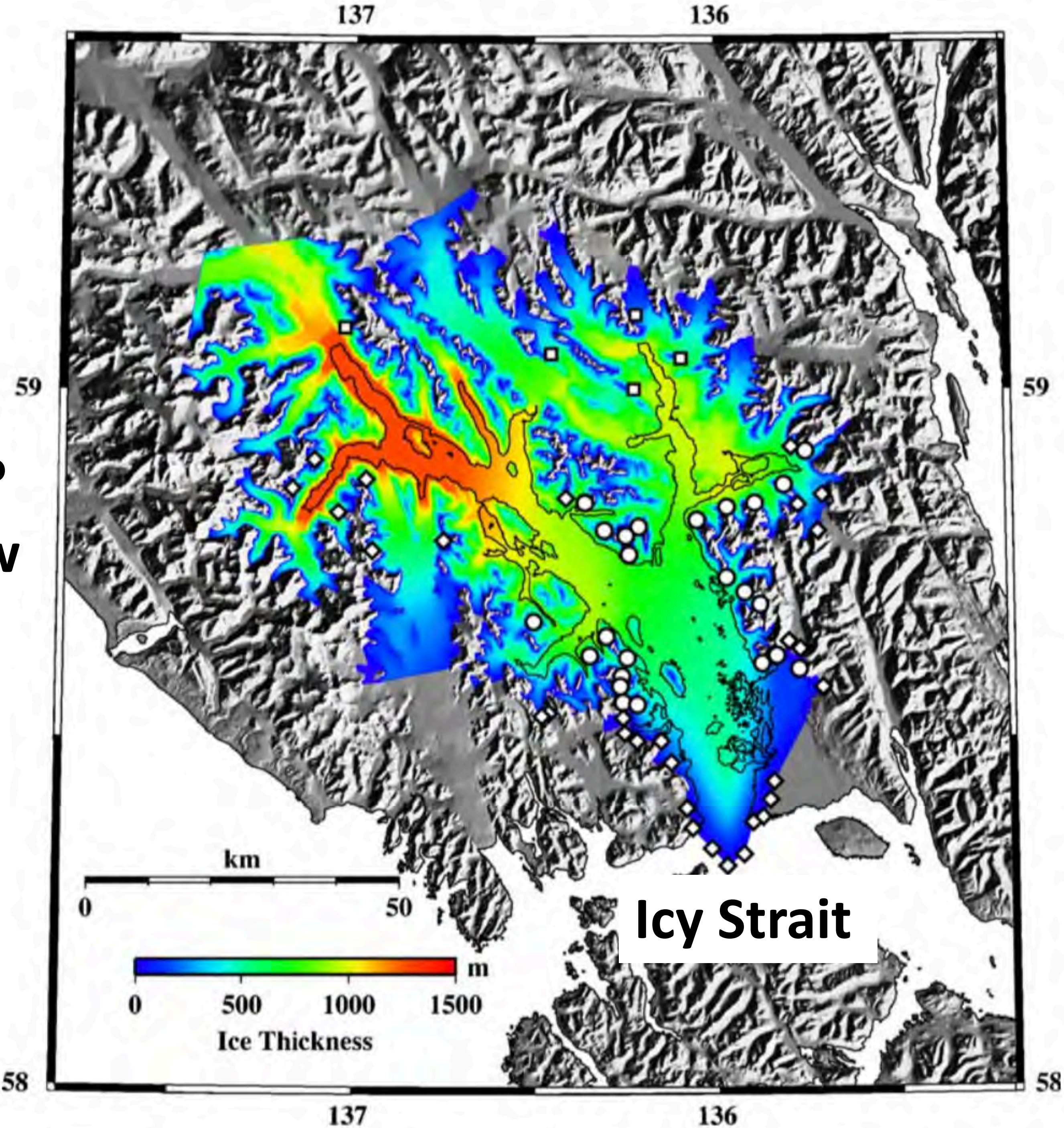
https://earthobservatory.nasa.gov/images/88701/glacier-bay-national-park-preserve https://soundwaves.usgs.gov/2001/07/glacierbaymap.gif



Muir Glacier, Alaska, August 13, 1941, photo by W.O. Field

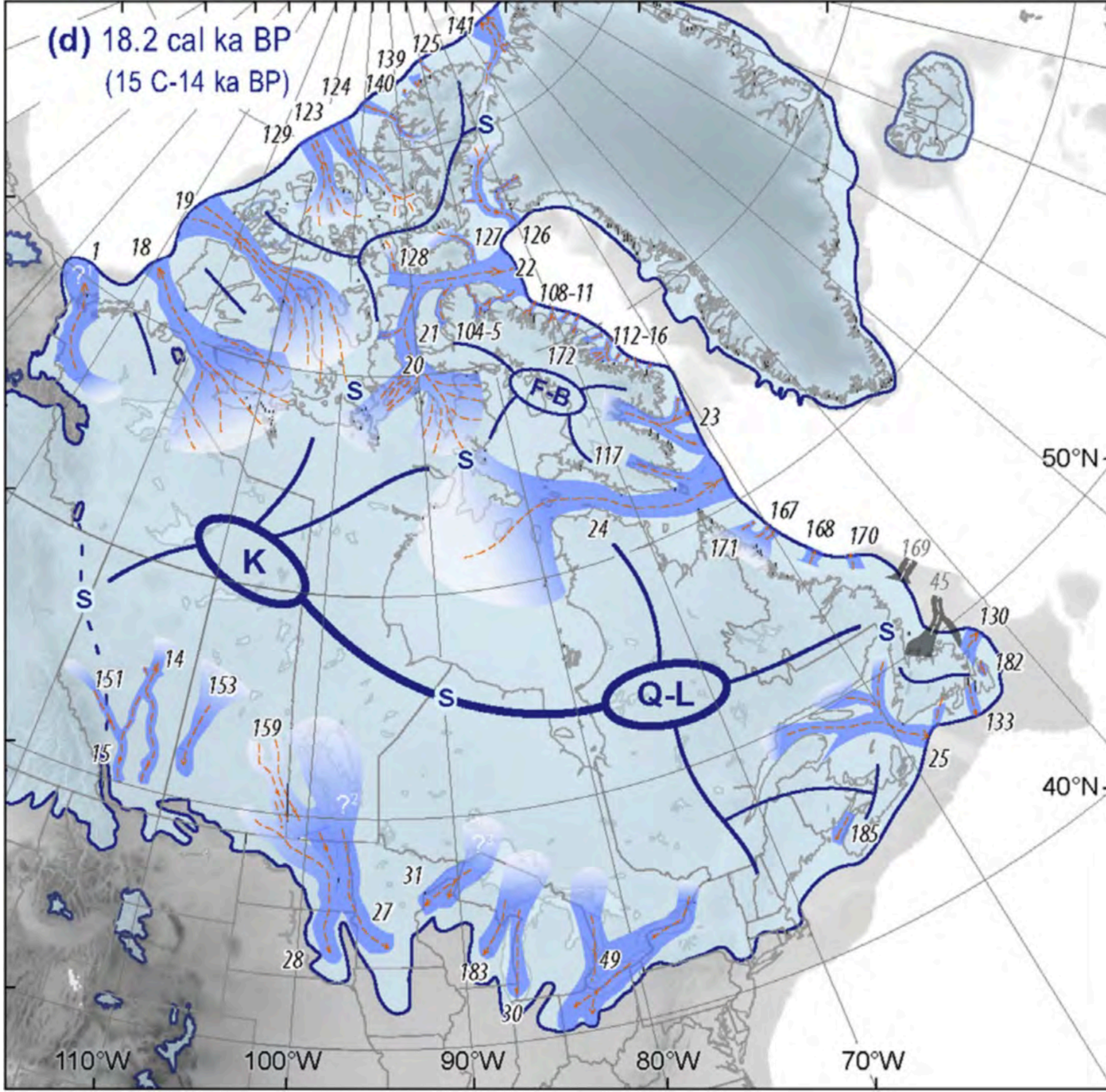
Muir Glacier, Alaska, August 31, 2004, photo by B.F. Molnia

Δ Ice thickness
~1500 m max
NOT by flow
to Icy Strait
105 km retreat
Peak ~1 km/yr?
Shallow, narrow
compared to
polar outlets

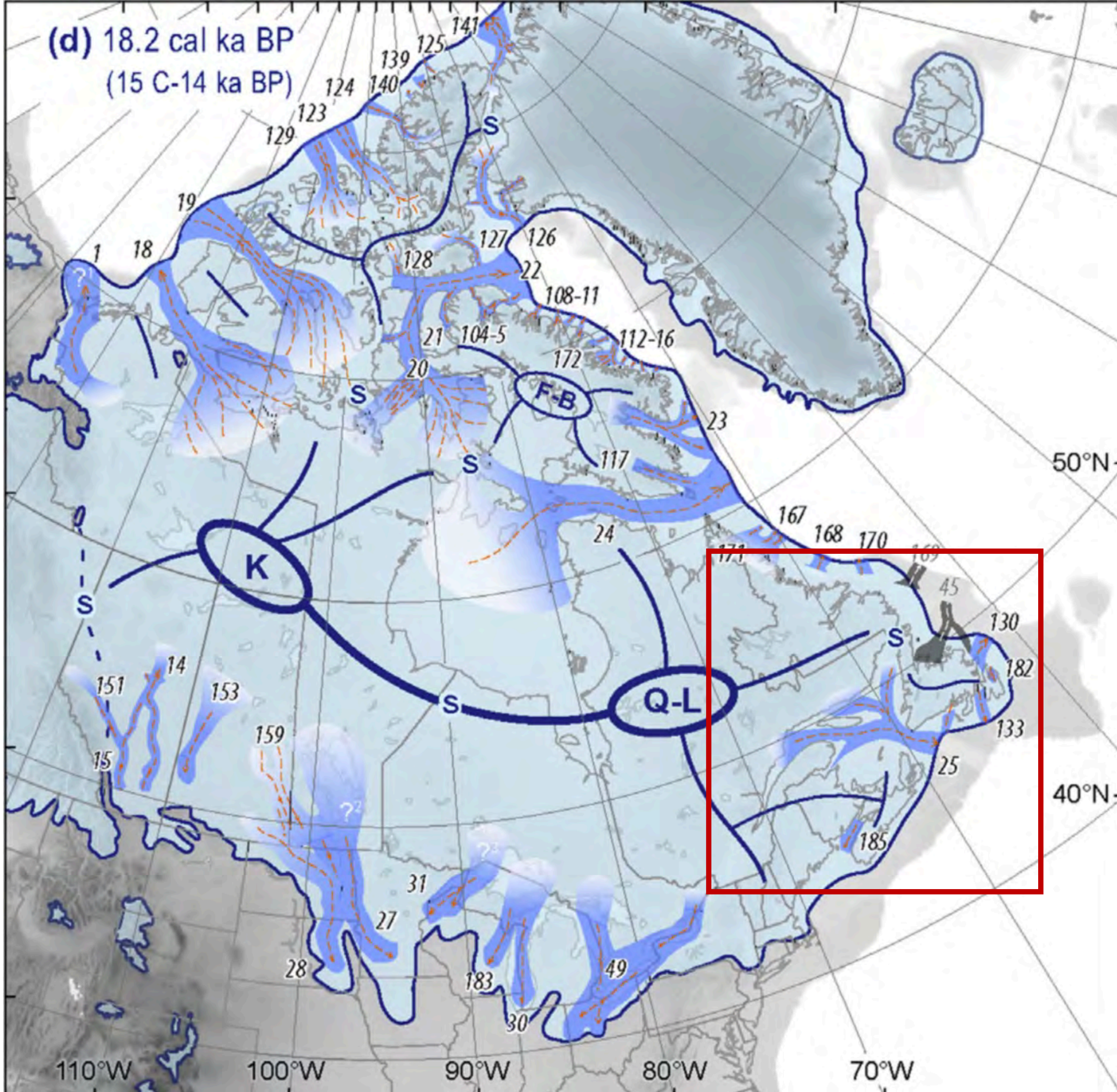


C.F. Larsen et al. / Earth and Planetary Science Letters 237 (2005) 548–560

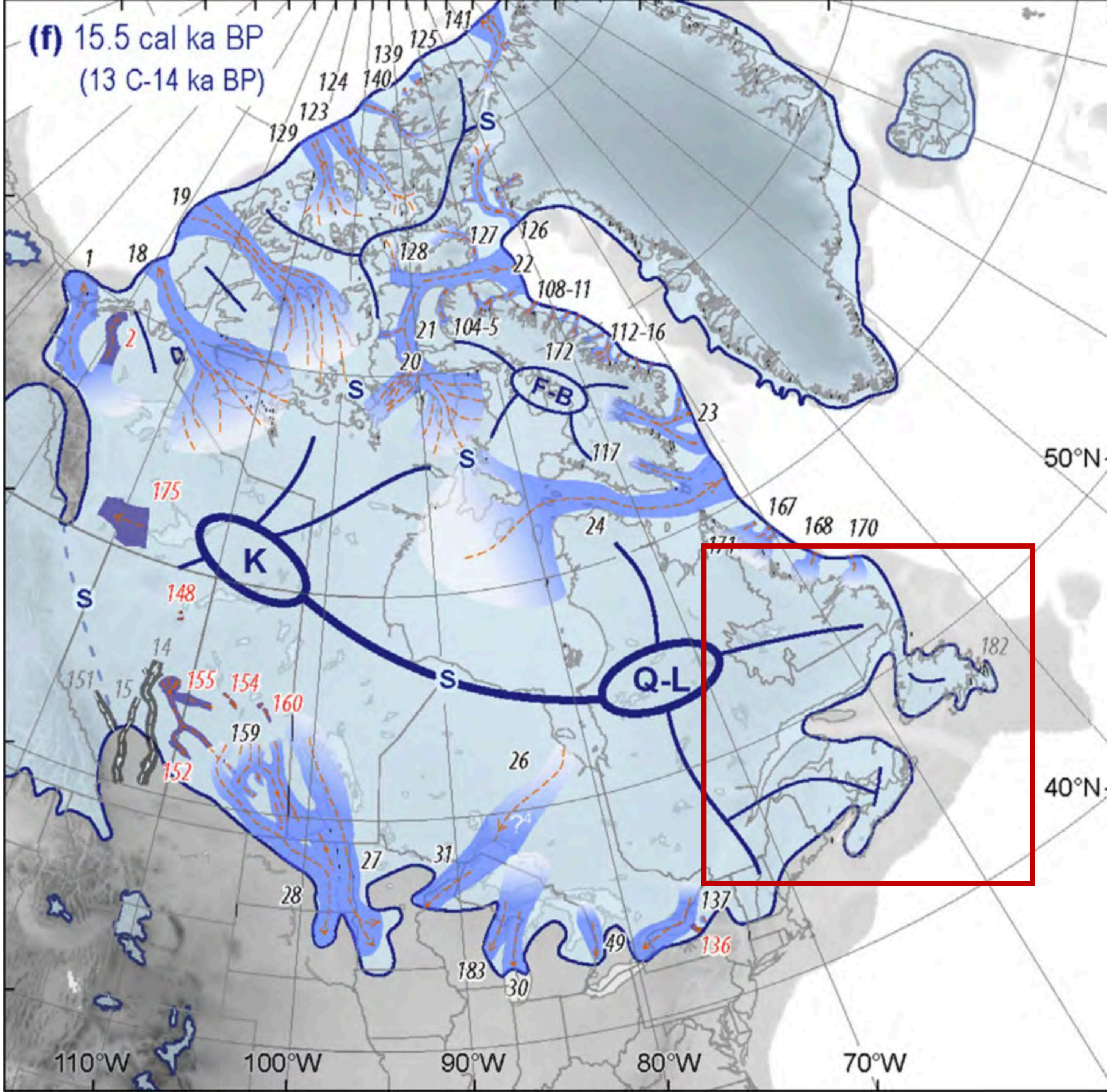
Margold, Stokes & Clark, QSR, 2018



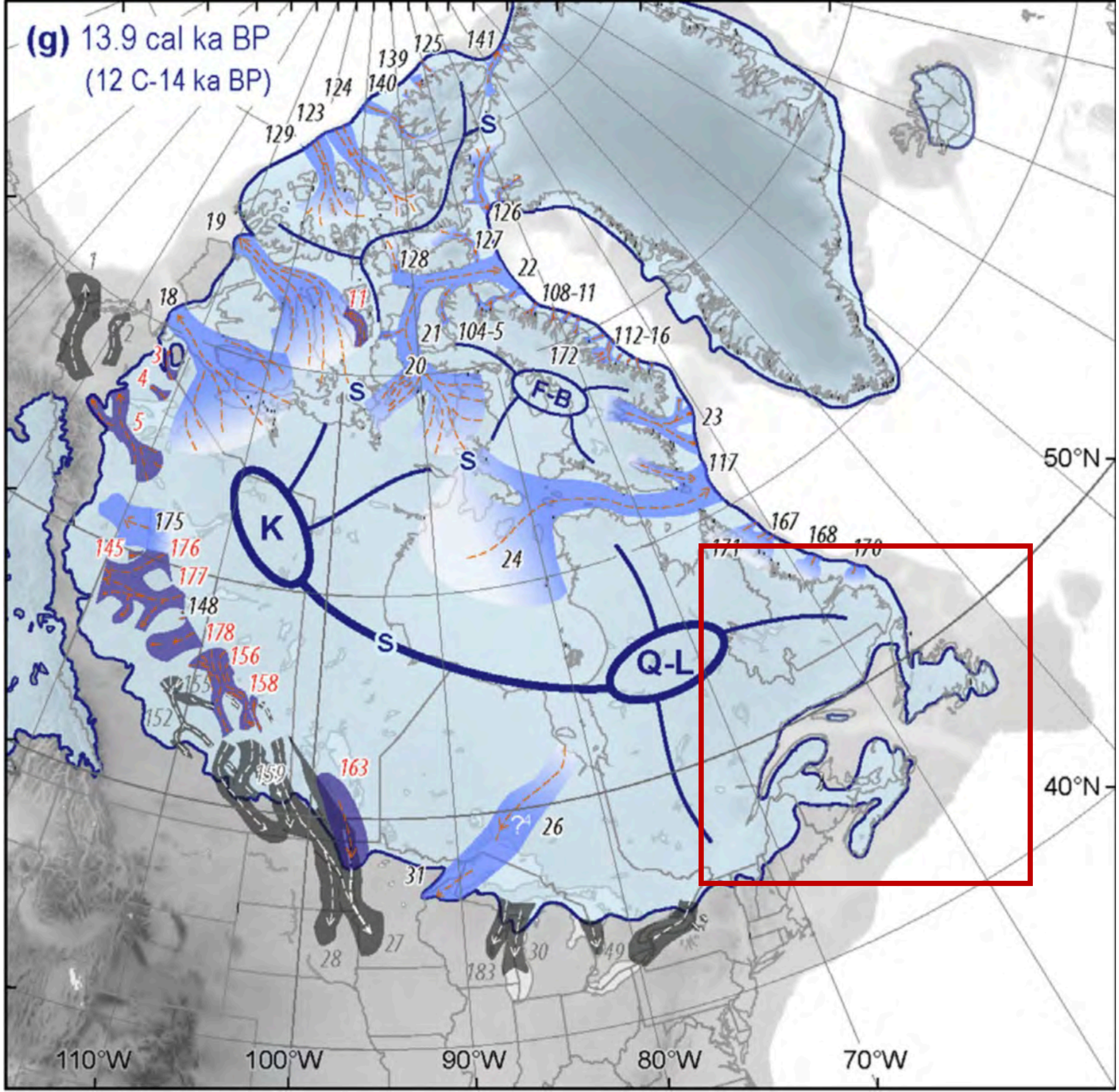
Margold, Stokes & Clark, QSR, 2018



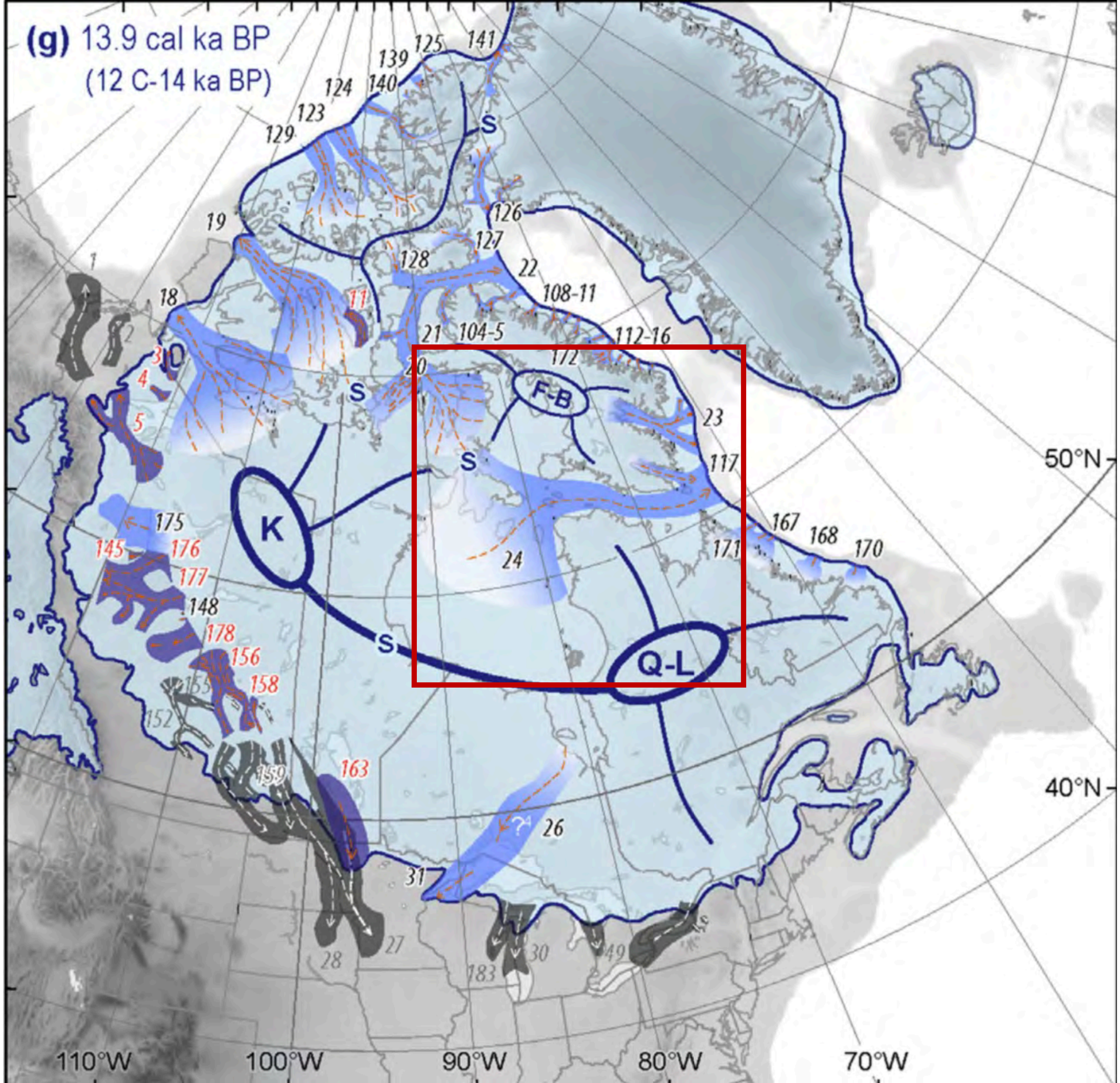
Margold, Stokes & Clark, QSR, 2018



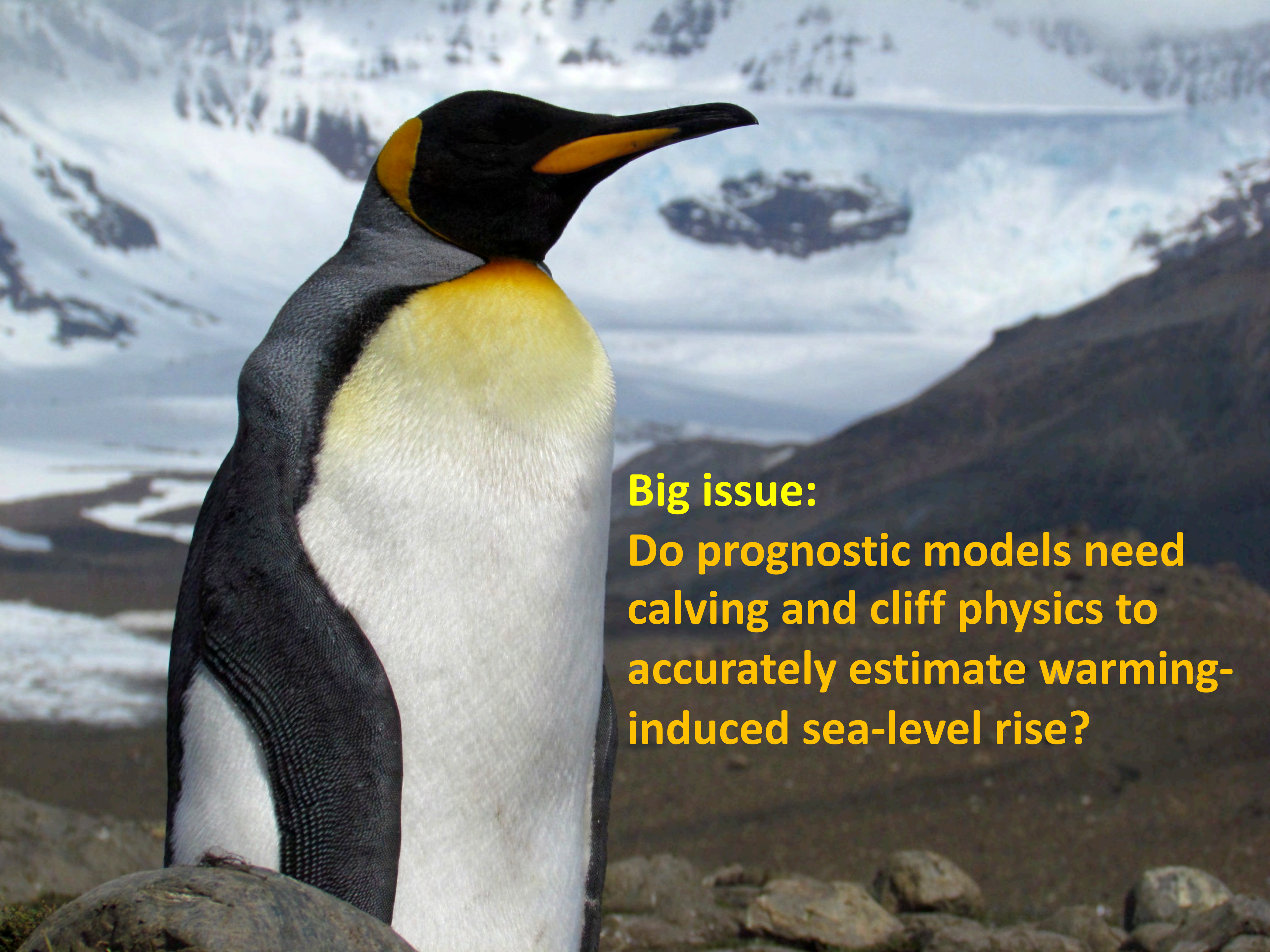
Margold, Stokes & Clark, QSR, 2018



Margold, Stokes & Clark, QSR, 2018

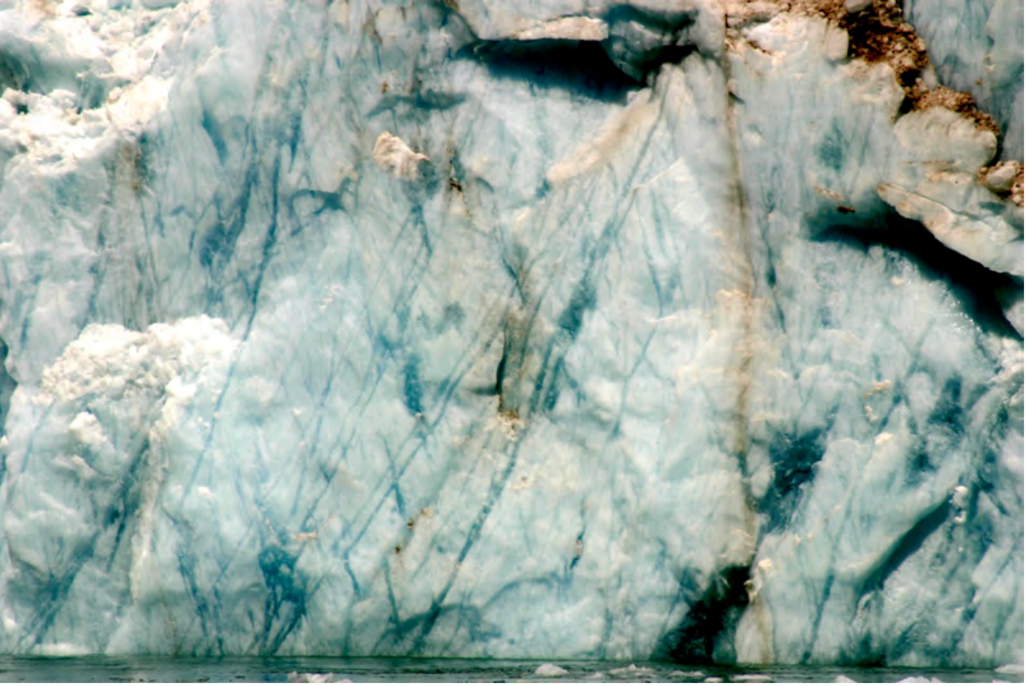


Margold,
Stokes &
Clark,
QSR,
2018


Big issue:
Do prognostic models need calving and cliff physics to accurately estimate warming-induced sea-level rise?

There are many places on land where you can walk up on the toe of a glacier…

which is what these Greenlandic wild reindeer did, to get away from tundra mosquitoes

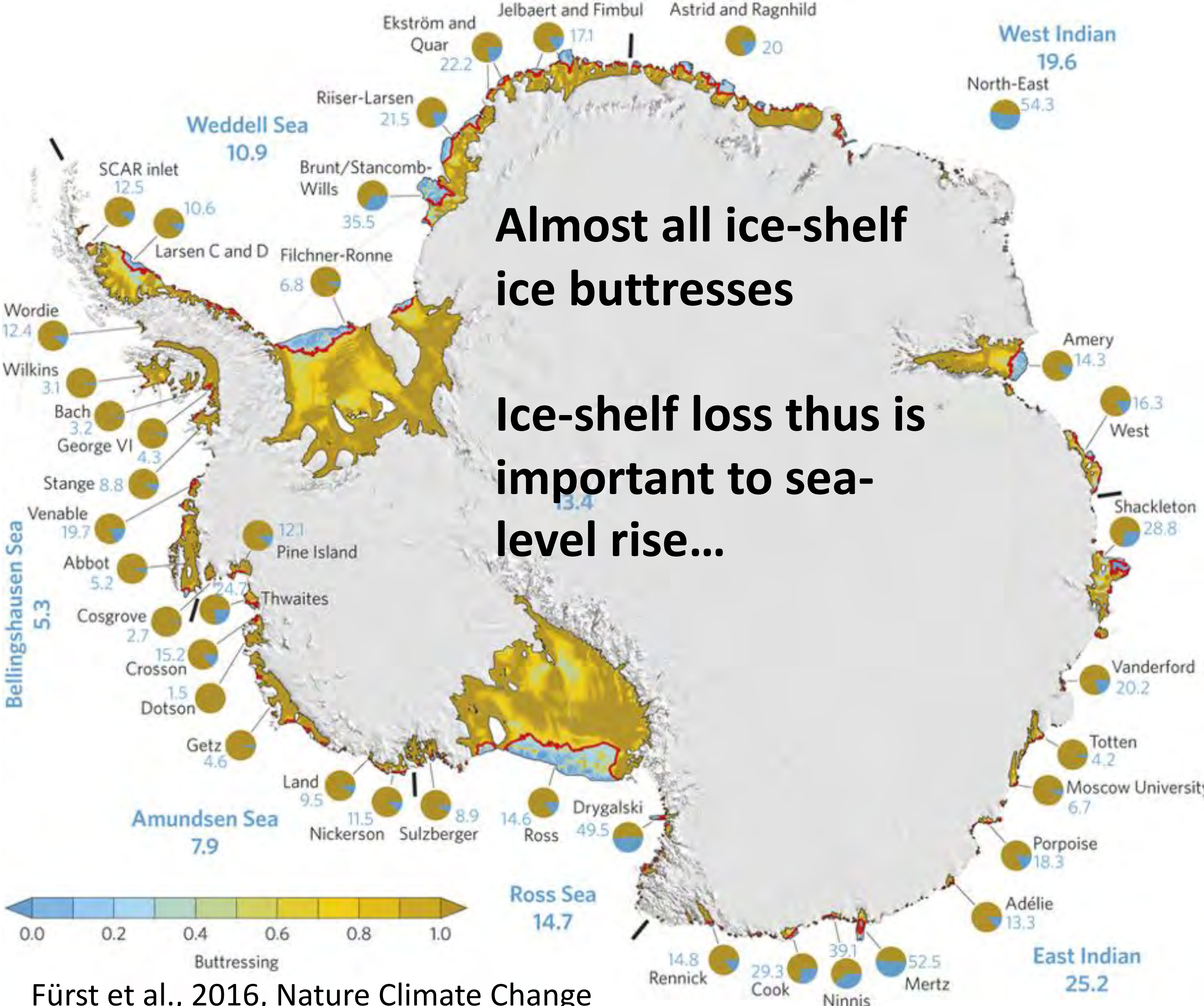


But you can't paddle your sea kayak to the ice front, jump out and walk up—almost all ice flowing into the ocean ends in a cliff, where fracture dominates

So, a reasonable hypothesis is that calving and cliff failure will continue to be important

Almost all ice-shelf ice buttresses

Ice-shelf loss thus is important to sea-level rise…

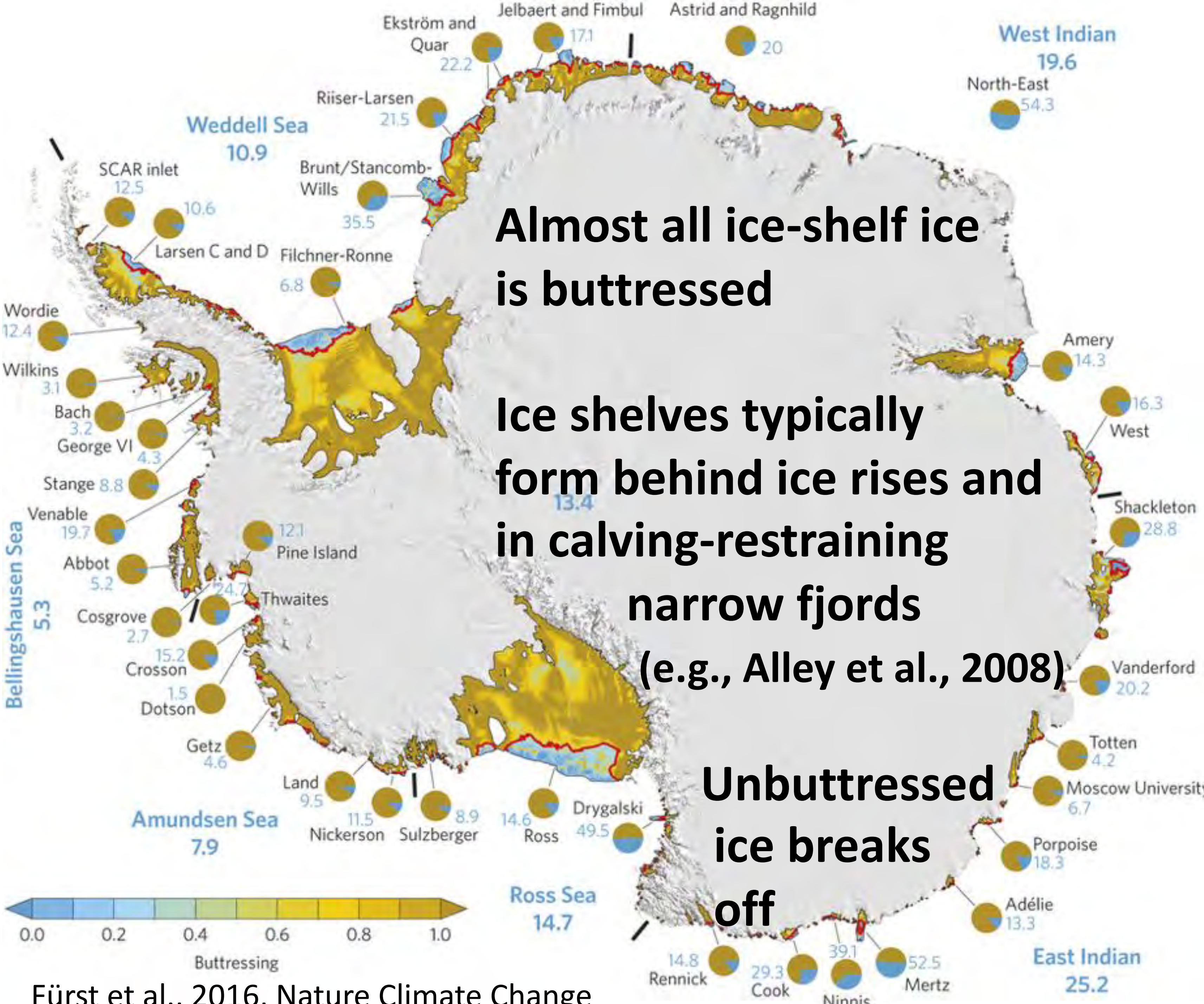


Fürst et al., 2016, Nature Climate Change

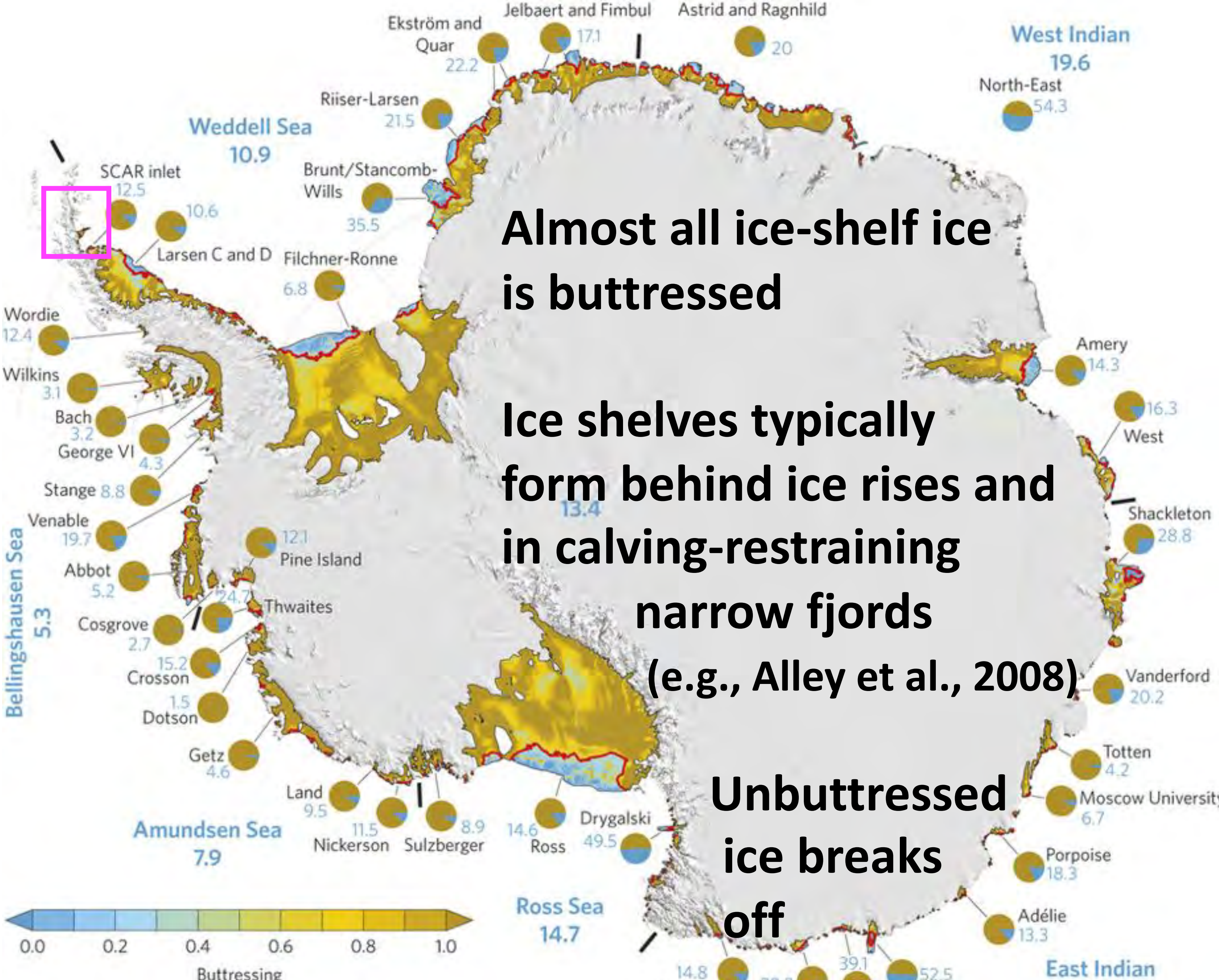
Almost all ice-shelf ice is buttressed

Ice shelves typically form behind ice rises and in calving-restraining narrow fjords (e.g., Alley et al., 2008)

Unbuttressed ice breaks off



Fürst et al., 2016, Nature Climate Change



Almost all ice-shelf ice is buttressed

Ice shelves typically form behind ice rises and in calving-restraining narrow fjords (e.g., Alley et al., 2008)

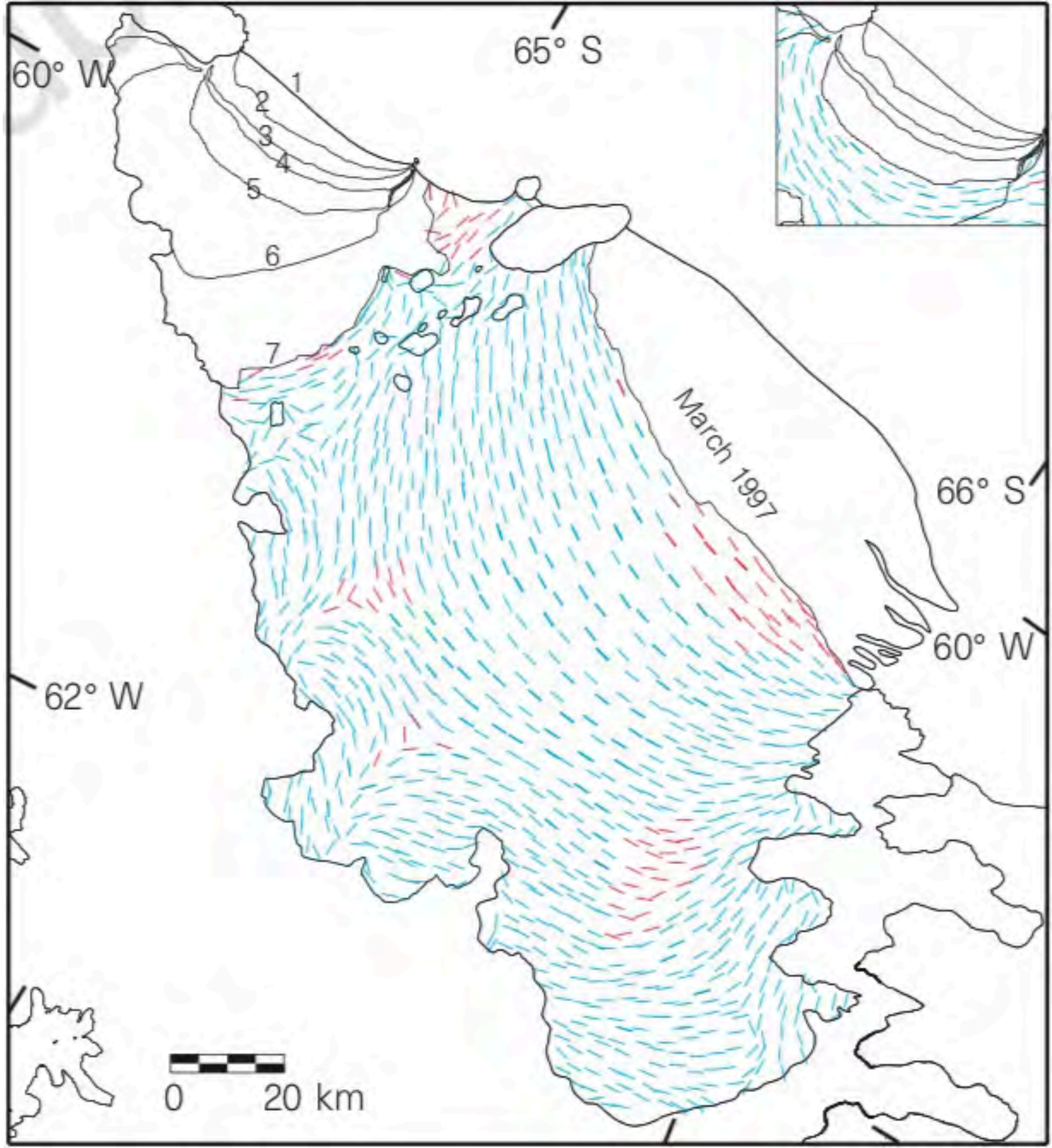
Unbuttressed ice breaks off

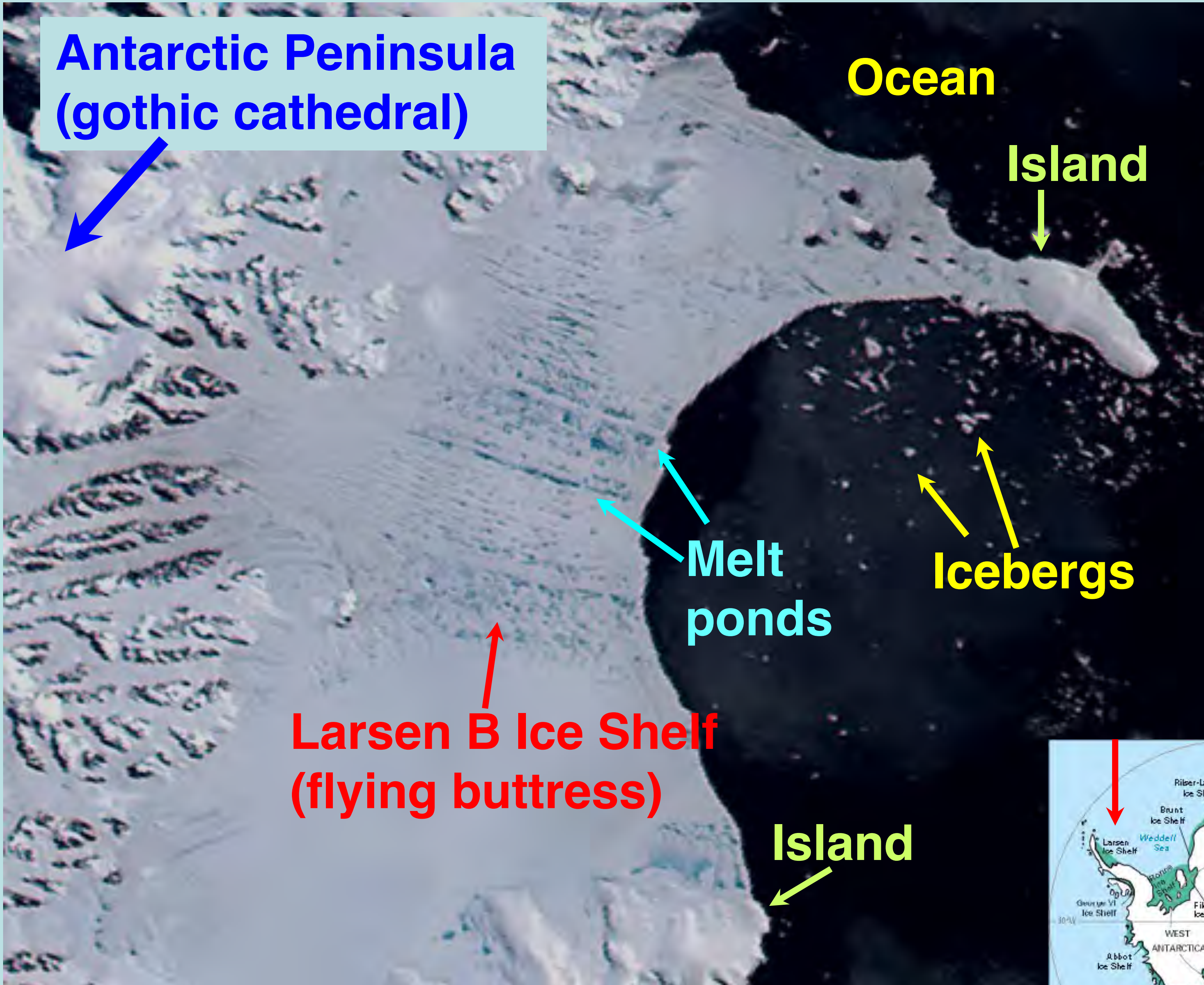
Fürst et al., 2016, Nature Climate Change

Doake et al., Nature, 1998

Successfully predicted Larsen B collapse

When some buttressing lost, ice shelves tend to break up completely



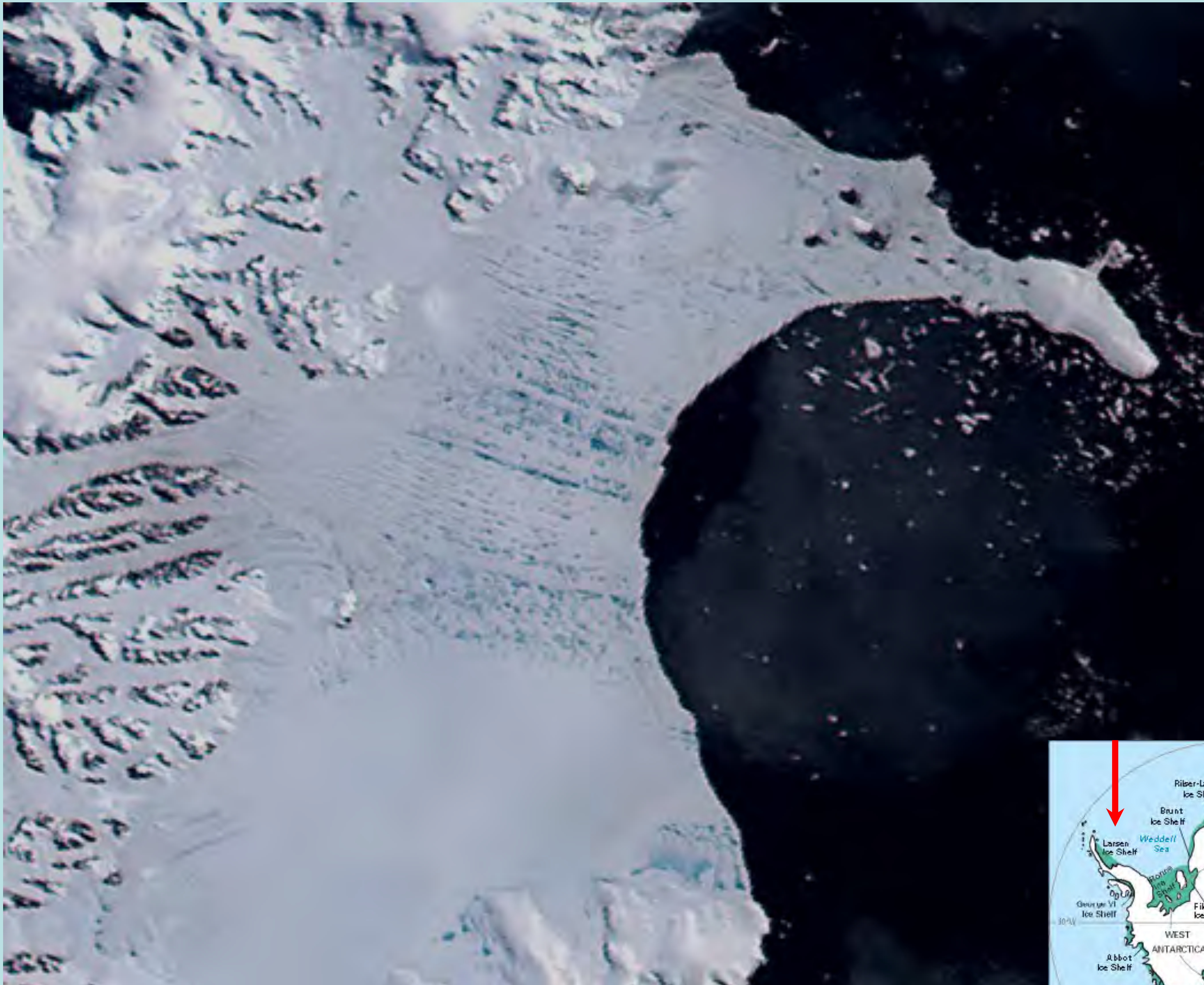


http://svs.gsfc.nasa.gov/vis/a000000/a002400/a002421/index.html

12 mi
20 km

January 31, 2002

http://svs.gsfc.nasa.gov/vis/a000000/a002400/a002421/index.html

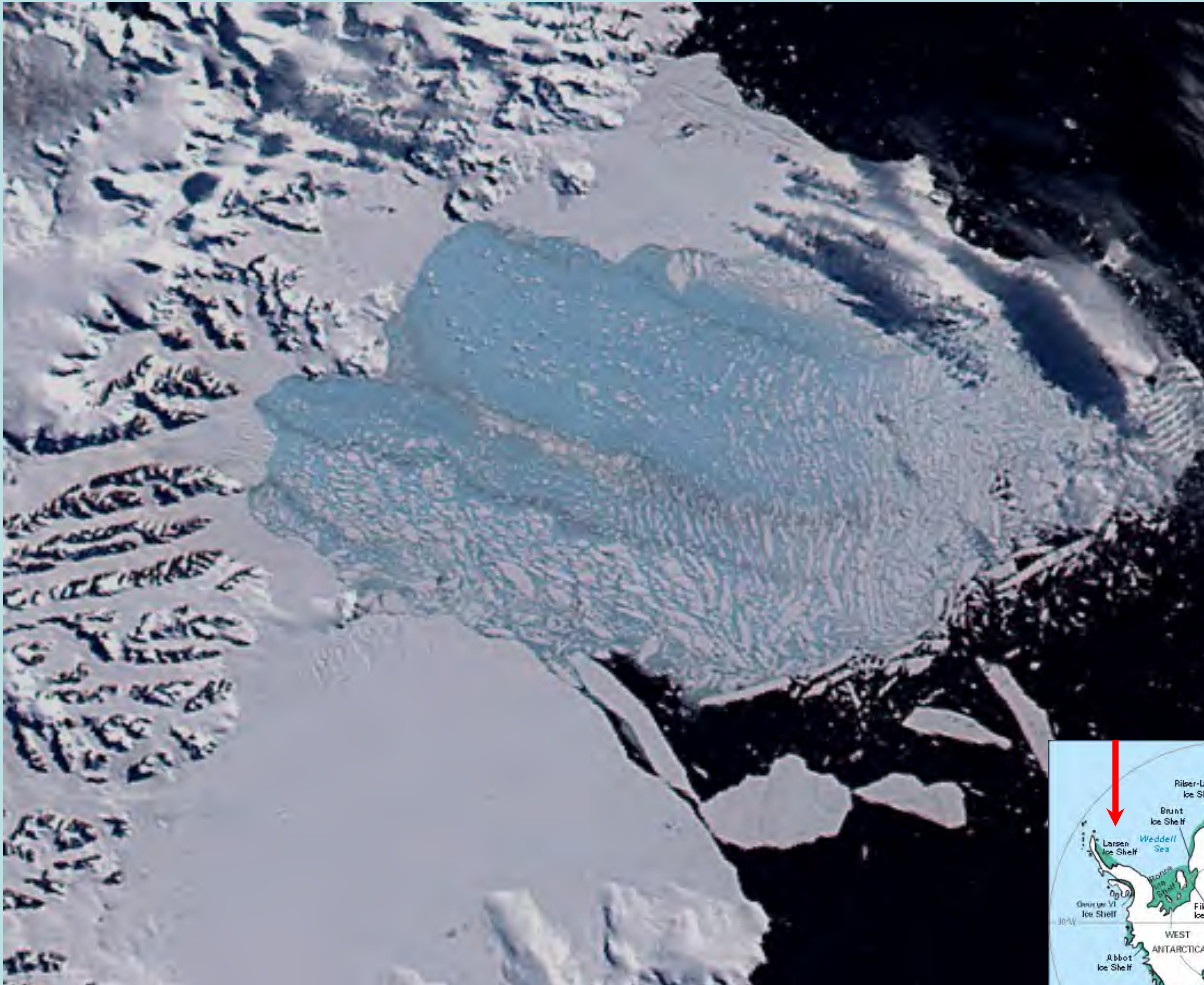


12 mi

20 km

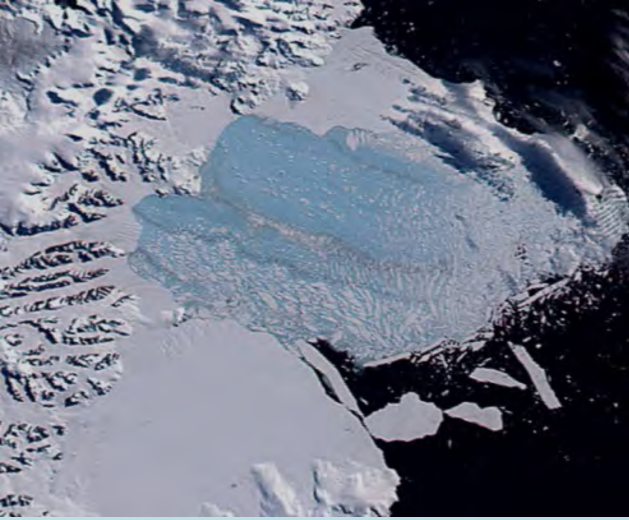
January 31, 2002

http://svs.gsfc.nasa.gov/vis/a000000/a002400/a002421/index.html



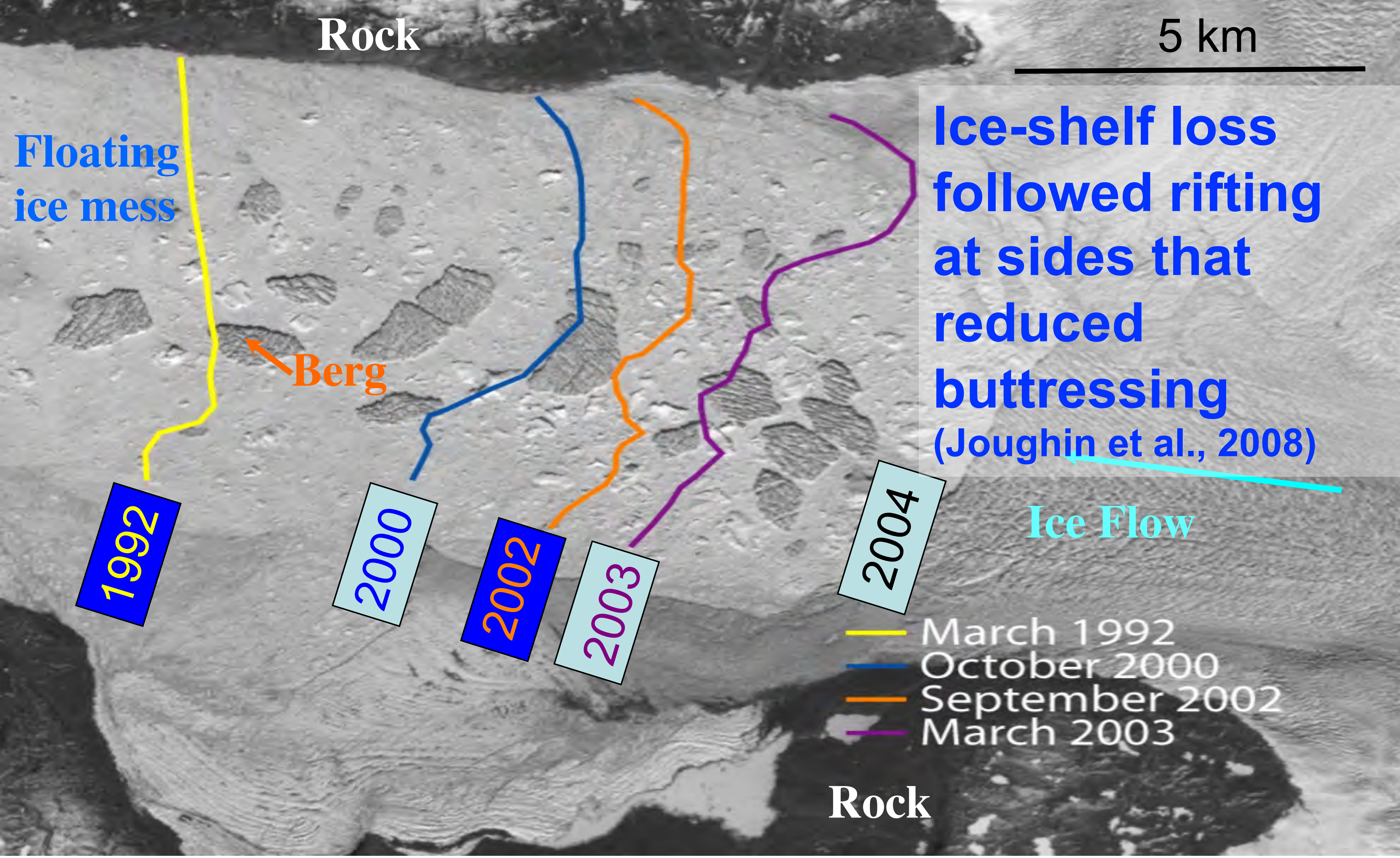
12 mi
20 km

March 7, 2002. **8x tributary flow-speed increase followed**



Not much ice behind Larsen B; loss can't raise sea level much

Many more ice shelves with lots of ice behind them that can raise sea level a lot.



Jakobshavn Isbrae retreat and speed doubling from ocean-warming-induced ice-shelf loss Ian Joughin (Alley et al., 2005).

We've seen ice shelves fall apart, and not grow back

Jakobshavn, Helheim try to re-grow, favored by:

- →cold ice, so strong
- →much thicker than surface-crevasse depth
- →moulin drainage inland keeps water out of crevasses (Parizek et al., 2010)
- →narrow fjords give stabilizing side shear, restrict wave forcing, aid mélange formation
- →flow so fast that can grow an ice shelf in a winter
- →fluctuations in climate give colder years

But shelves still fail to re-grow

Hysteresis—breaking easier than building

So we see in multiple cases

→Warming (air and/or water) reduces shelf buttressing

→Shelf then breaks off, leaving a grounded calving cliff

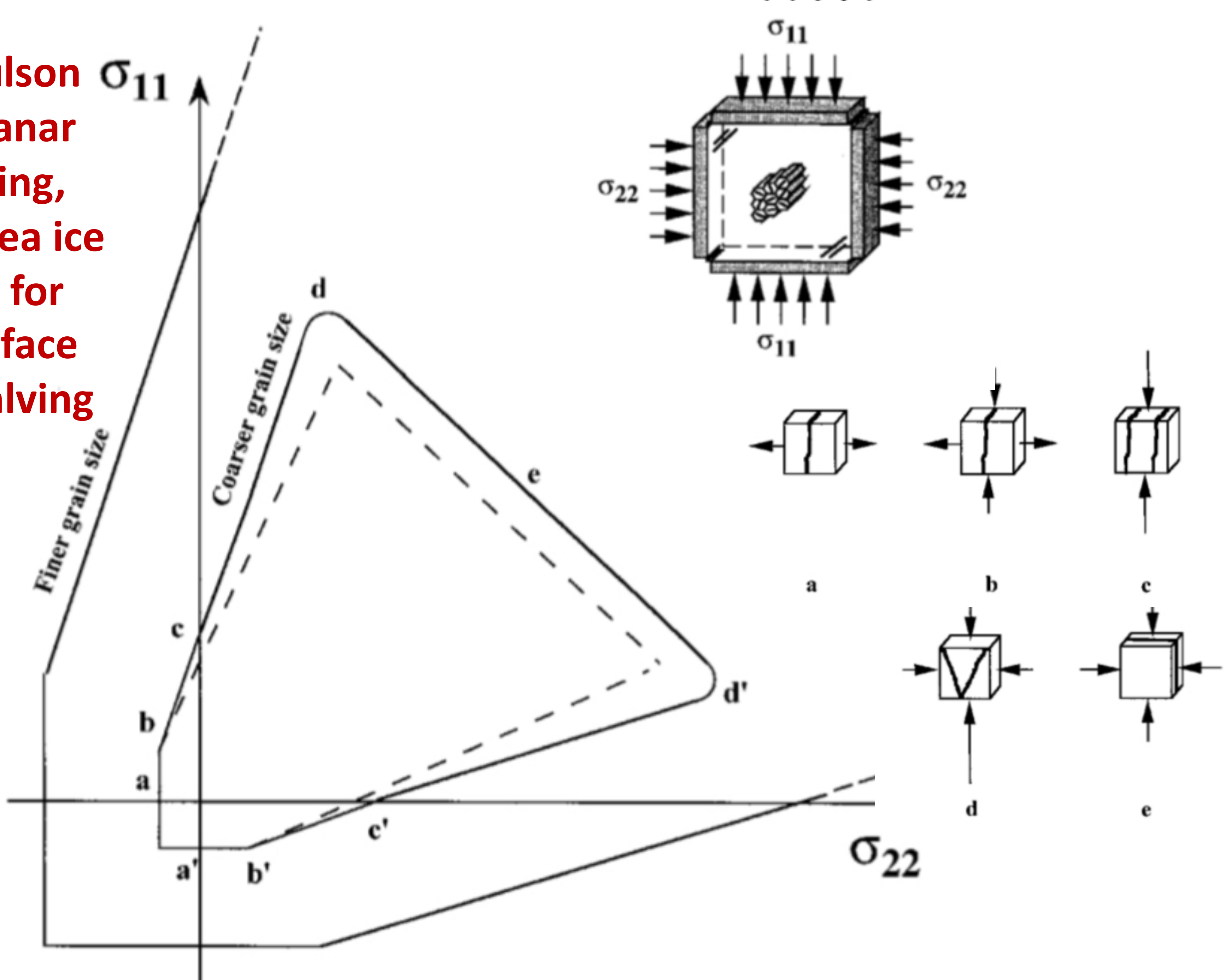
→Ice flow accelerates

→And the shelf stays off

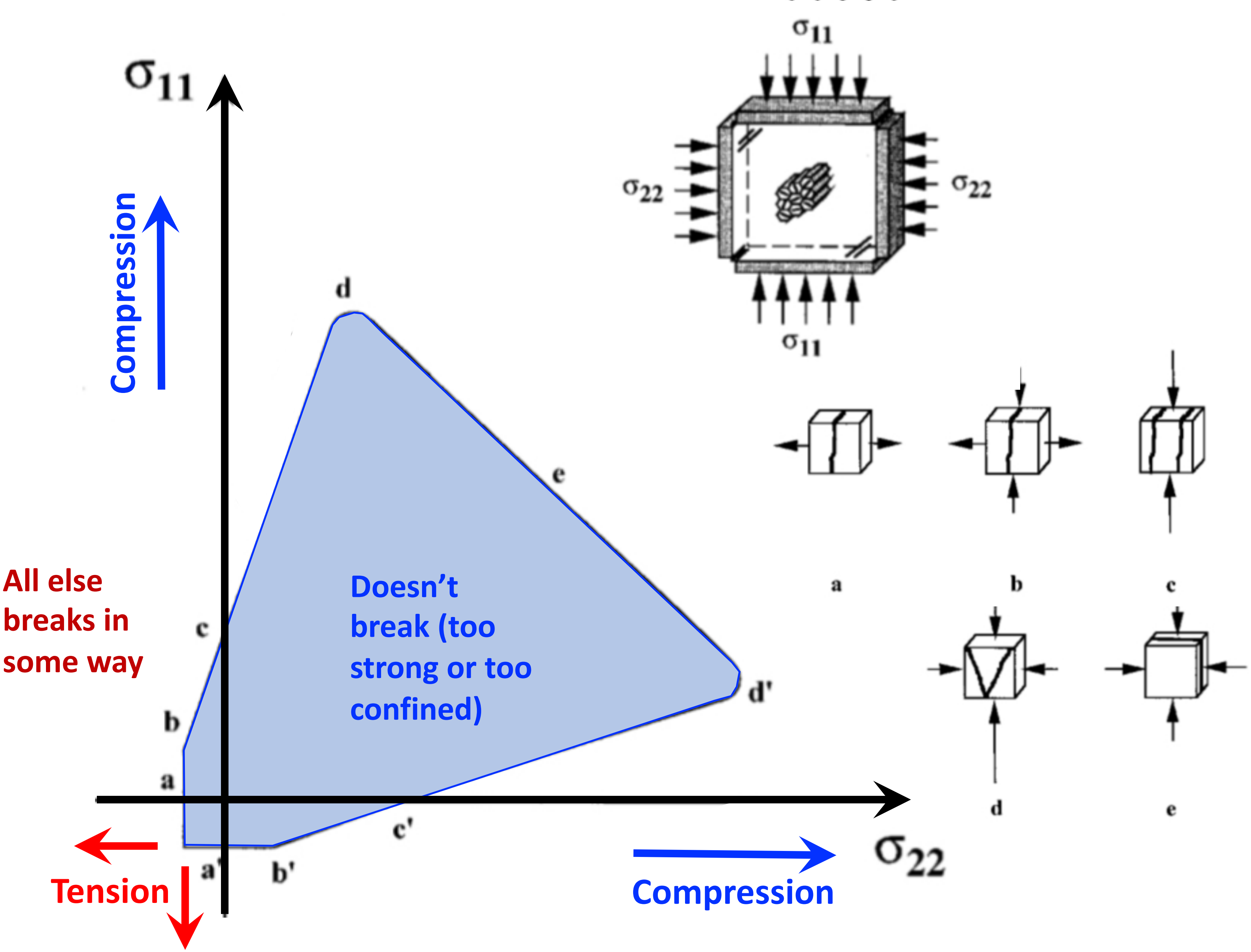

All cliff ice is relaxing by creep, but is breaking faster


Could higher future cliffs relax fast enough to re-form ice shelves?

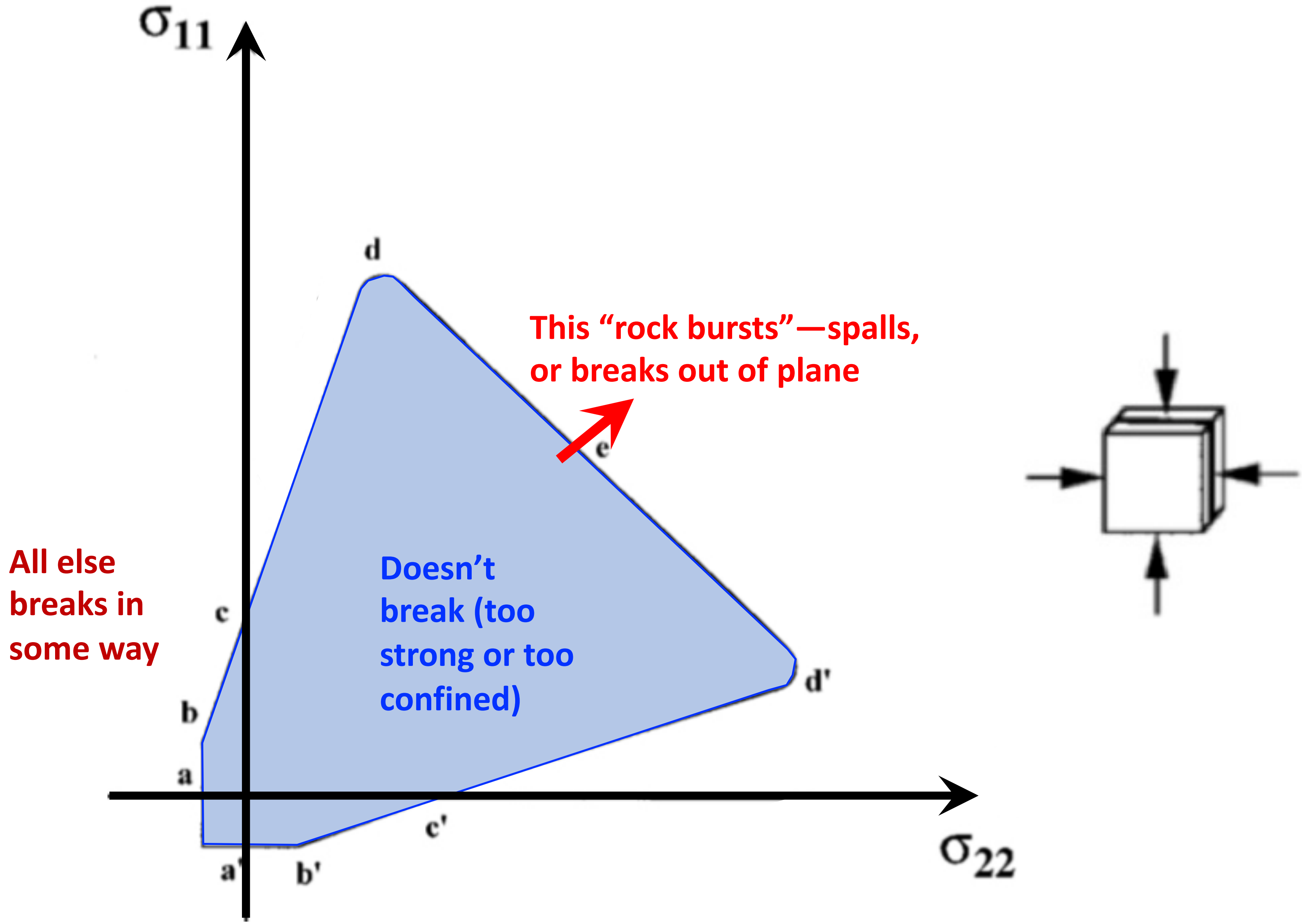
Schulson—planar loading, for sea ice (and for free face of calving cliff)



Schulson, 2001, Engr. Fract. Mech.

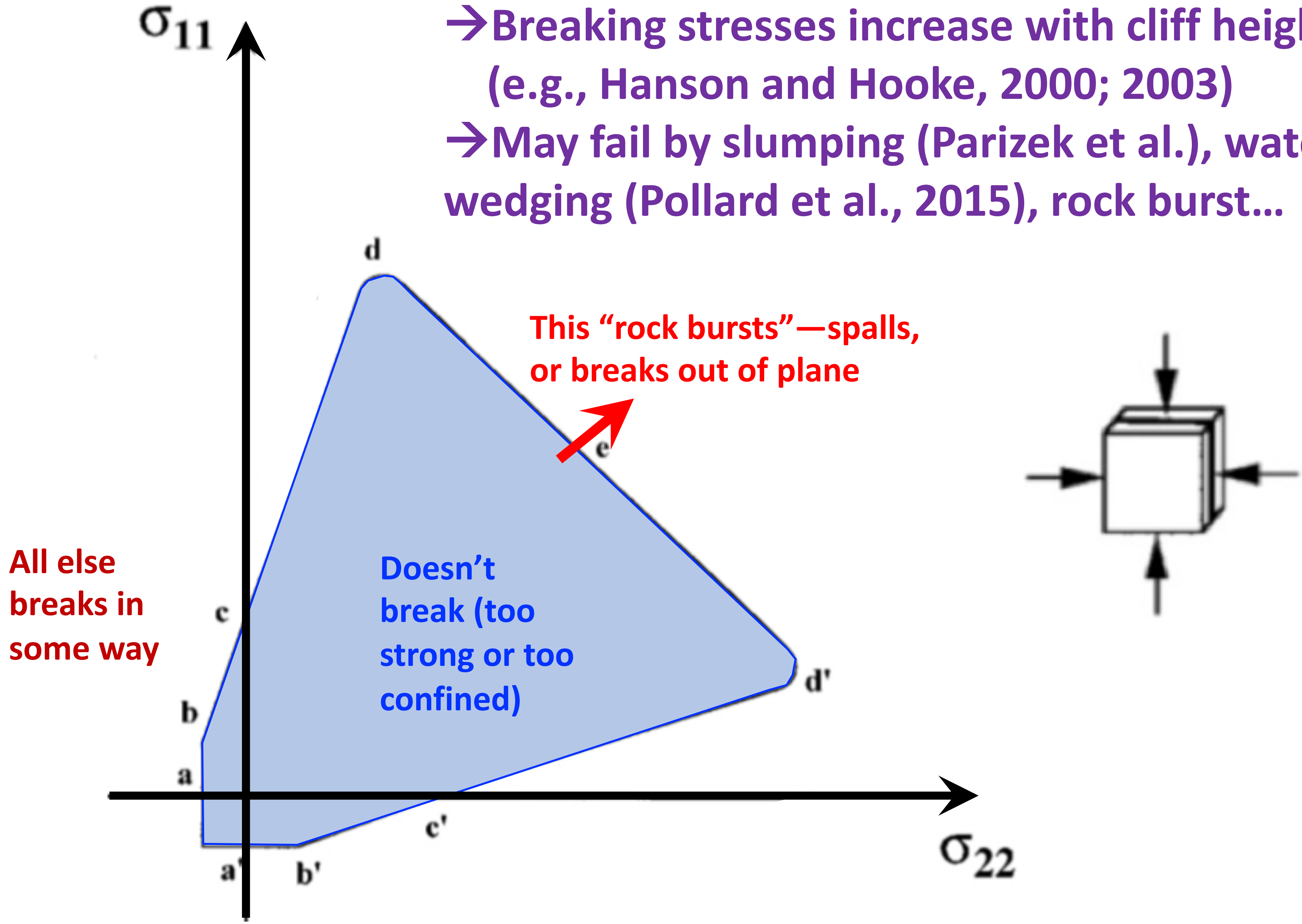


Schulson, 2001, Engr. Fract. Mech.



Schulson, 2001, Engr. Fract. Mech.

→Free face of a cliff prevents confinement
→Breaking stresses increase with cliff height (e.g., Hanson and Hooke, 2000; 2003)
→May fail by slumping (Parizek et al.), water wedging (Pollard et al., 2015), rock burst…



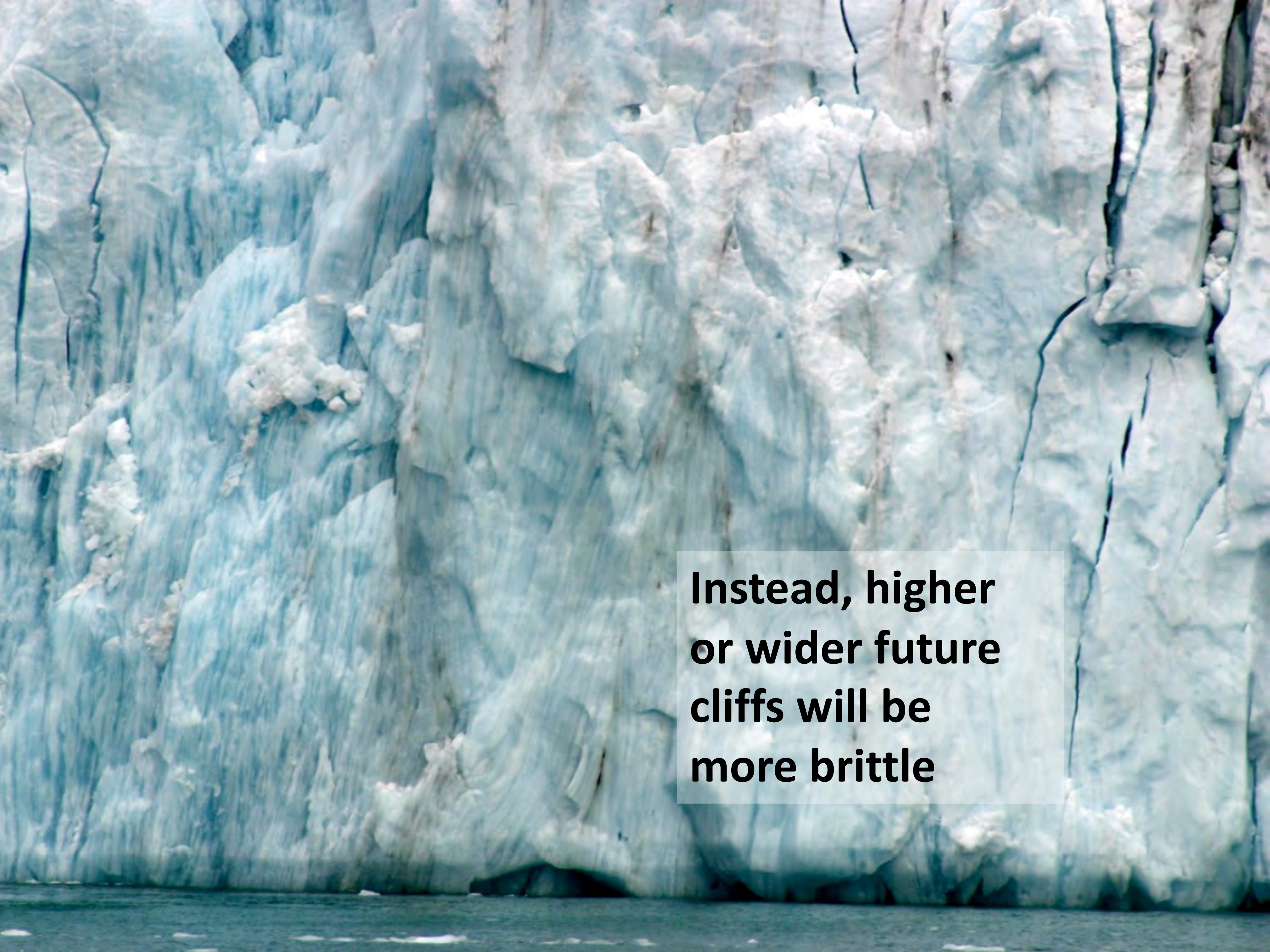
Schulson, 2001, Engr. Fract. Mech.

If creep and subcritical cracking are occurring at a similar rate, 2x cliff height→2x deviatoric stress causing deformation: creep increases ~10x; cracking increases ~10^9x

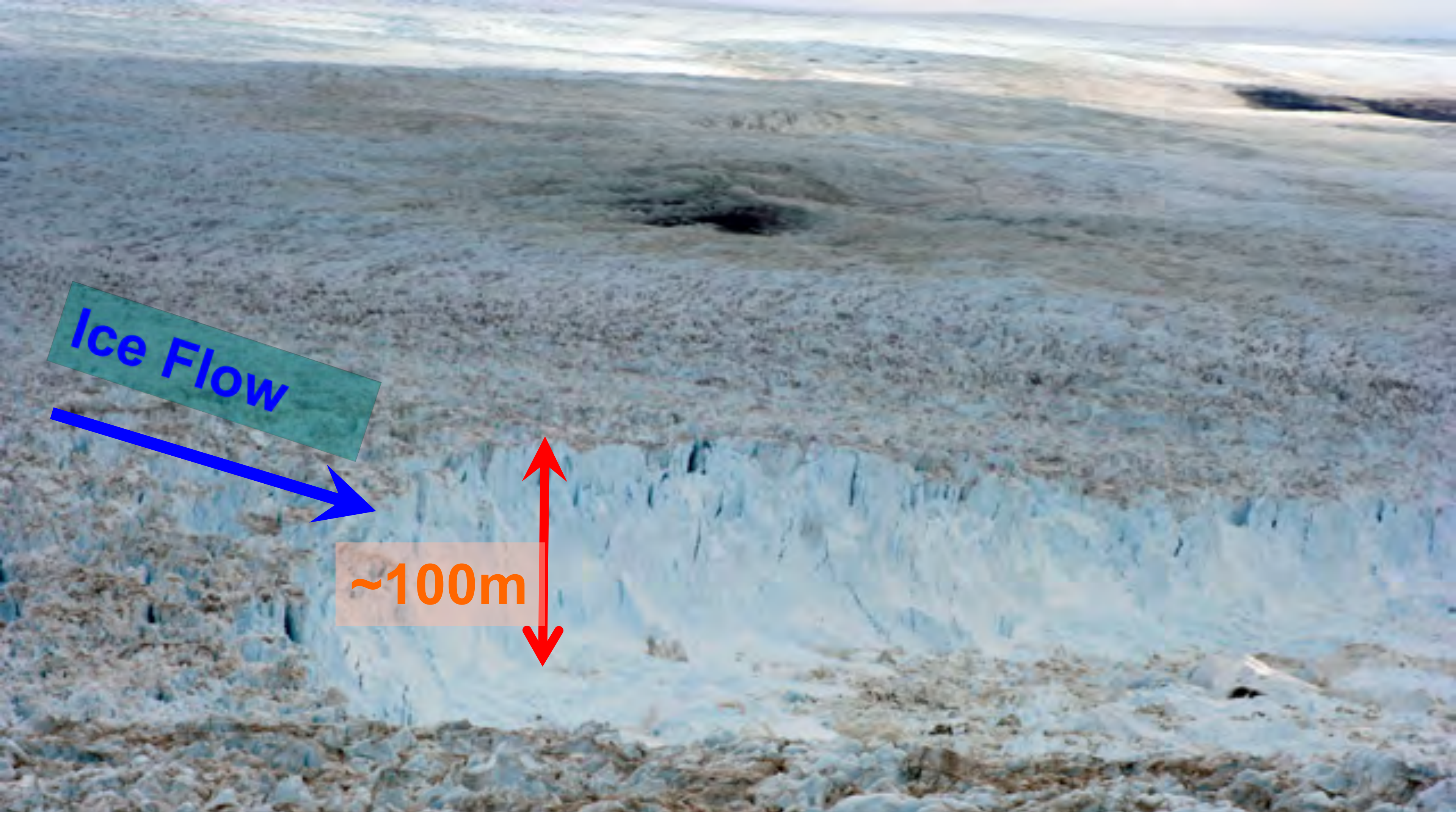
If creep and subcritical cracking are occurring at a similar rate, doubling deviatoric stress causing deformation:
creep increases ~10x; cracking increases ~10^9x

Brittle-to-ductile or flow-to-fracture transition

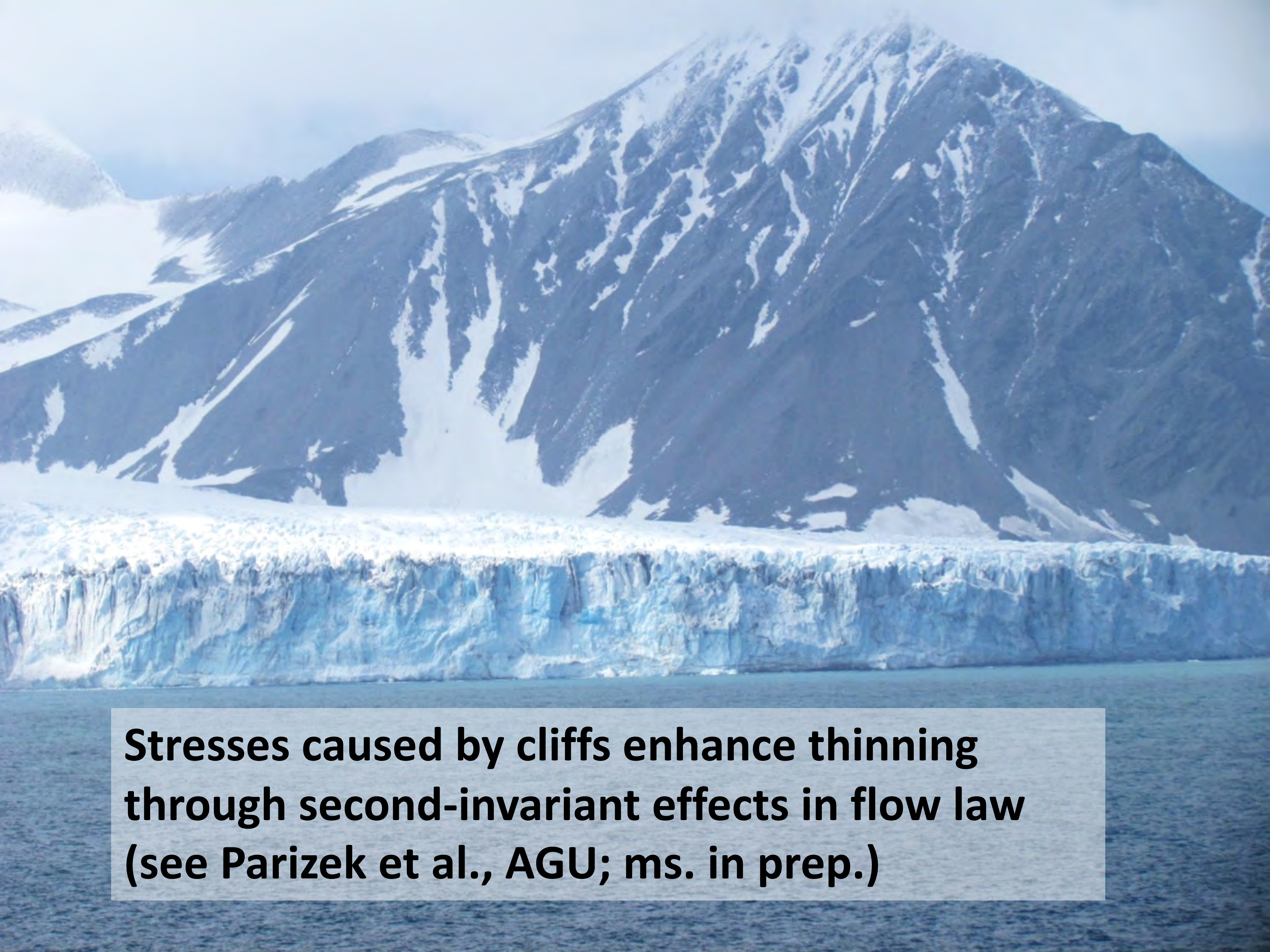

Could higher future cliffs relax fast enough to re-form ice shelves? No


Instead, higher or wider future cliffs will be more brittle

But does it matter? Yes...

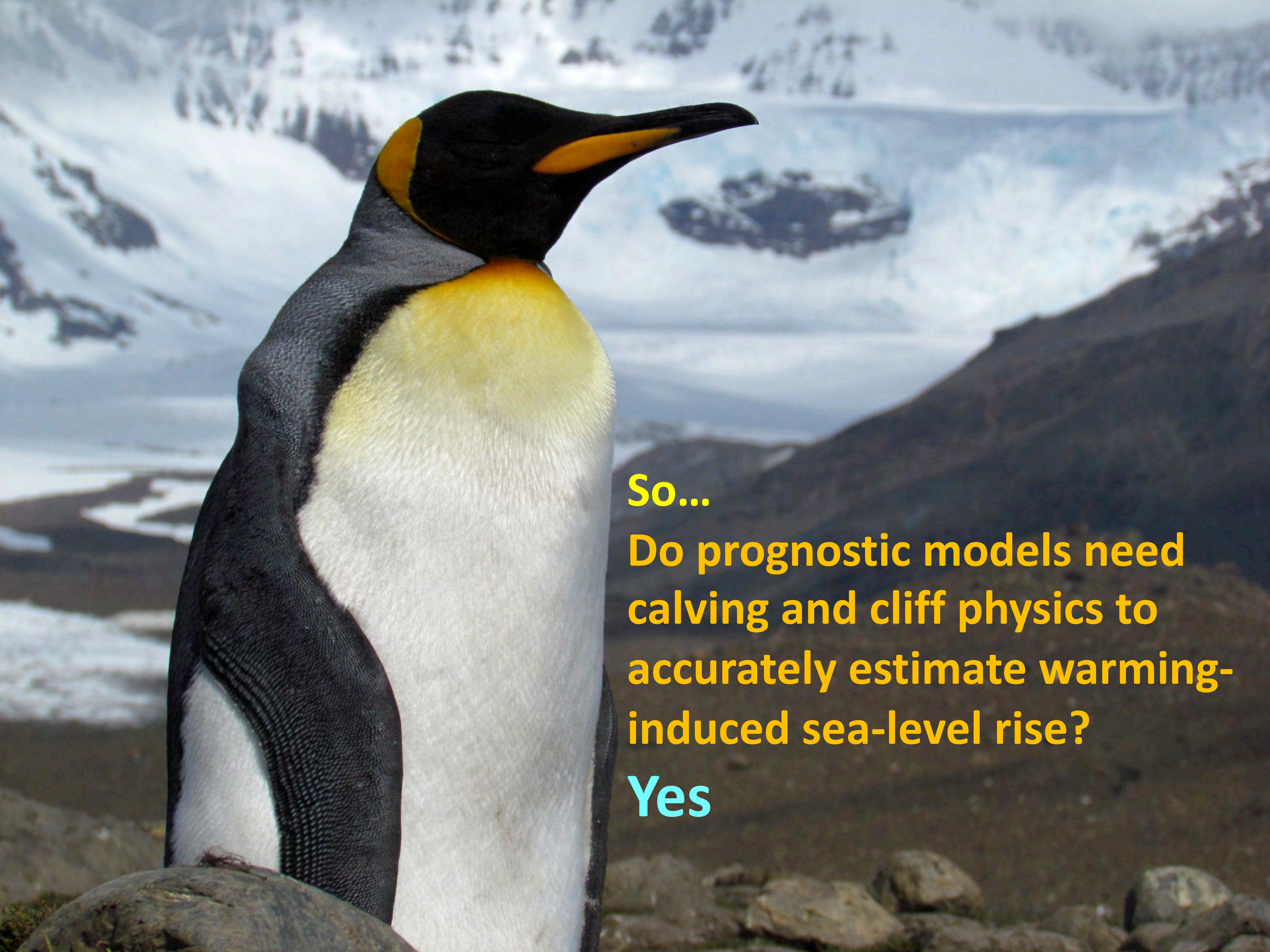


Jakobshavn calves to ~20 m thicker than flotation, reducing drag, speeding flow and thinning (Joughin et al., 2012)



Stresses caused by cliffs enhance thinning through second-invariant effects in flow law (see Parizek et al., AGU; ms. in prep.)


With very rapid failure by water-driven
crevassing, slumping, spalling for too-tall cliffs



So…

Do prognostic models need calving and cliff physics to accurately estimate warming-induced sea-level rise?

Yes

What can we do? Model calving and cliffs…

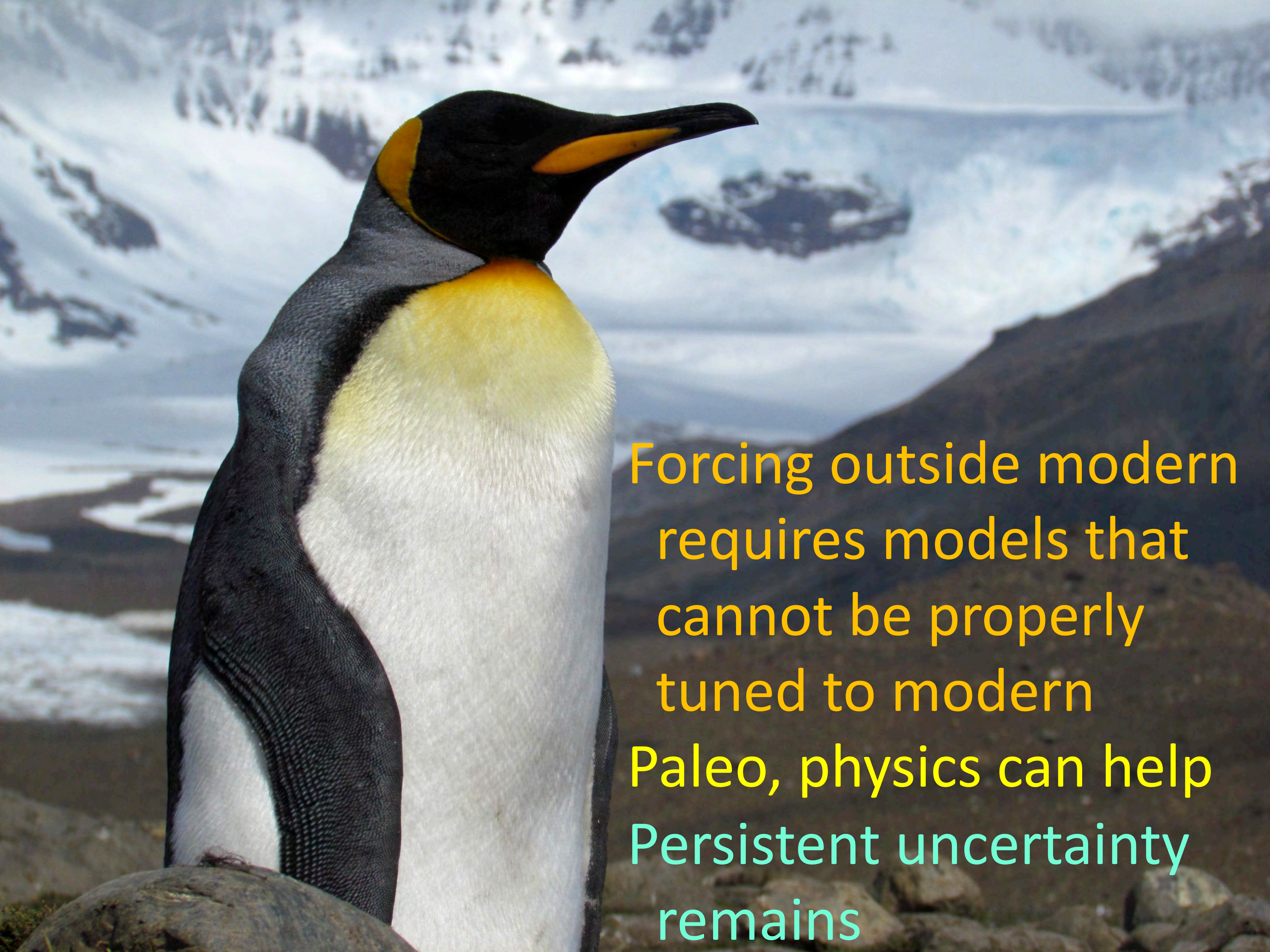
What can we do? Model calving and cliffs…Or:

→Set ice-shelf buttressing to zero above some temperature

→Set basal drag to zero a bit inland of flotation (calving to there)

→Weaken near-grounding-zone ice (second-invariant cliff effects)

→Set flag–if cliff much taller than 100 m, retreat faster than model


Forcing outside modern requires models that cannot be properly tuned to modern
Paleo, physics can help
Persistent uncertainty remains