Seismological constraints on glacial processes

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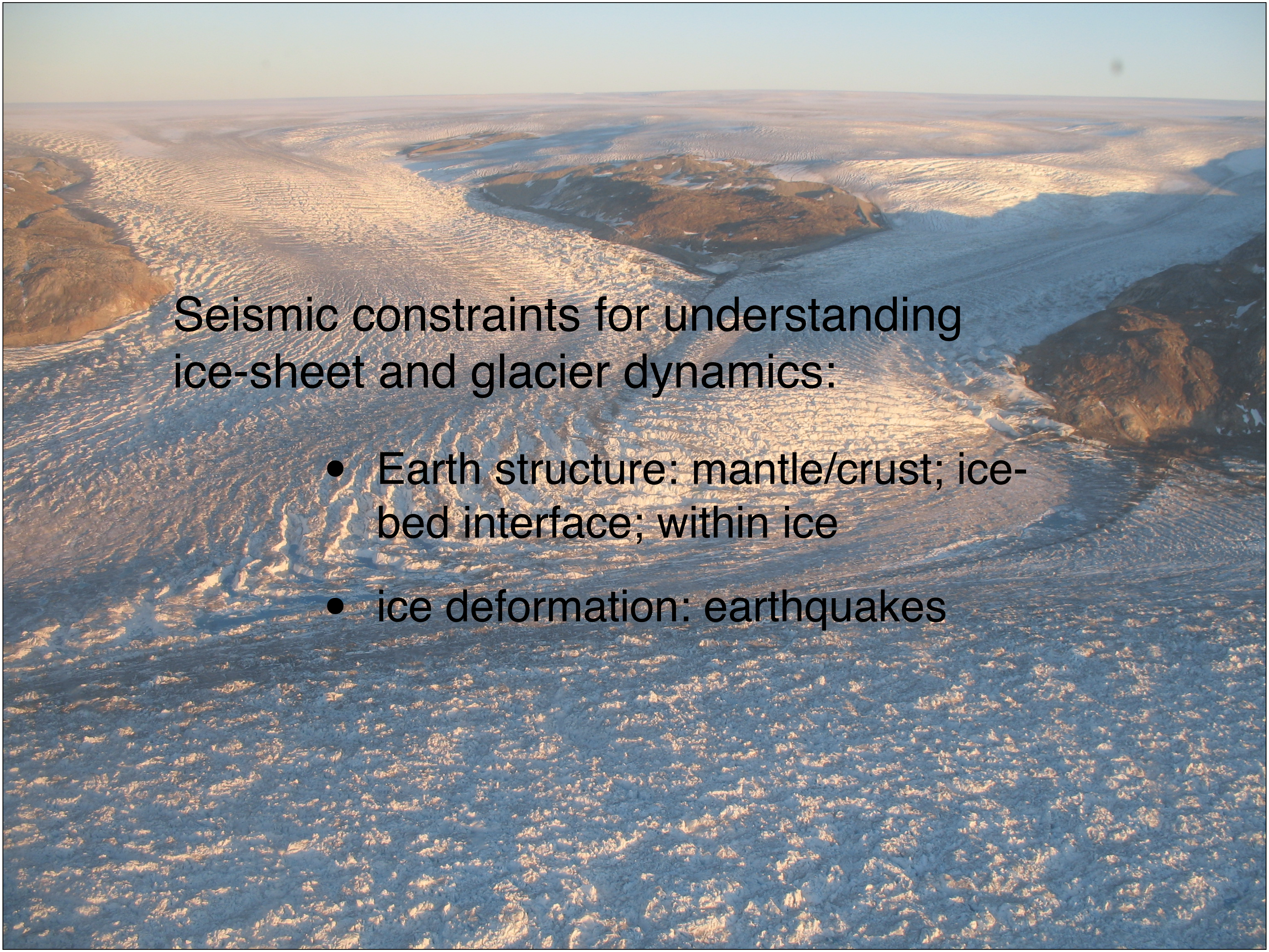


Seismic constraints for understanding ice-sheet and glacier dynamics:

- Earth structure: mantle/crust; ice-bed interface; within ice
- ice deformation: earthquakes

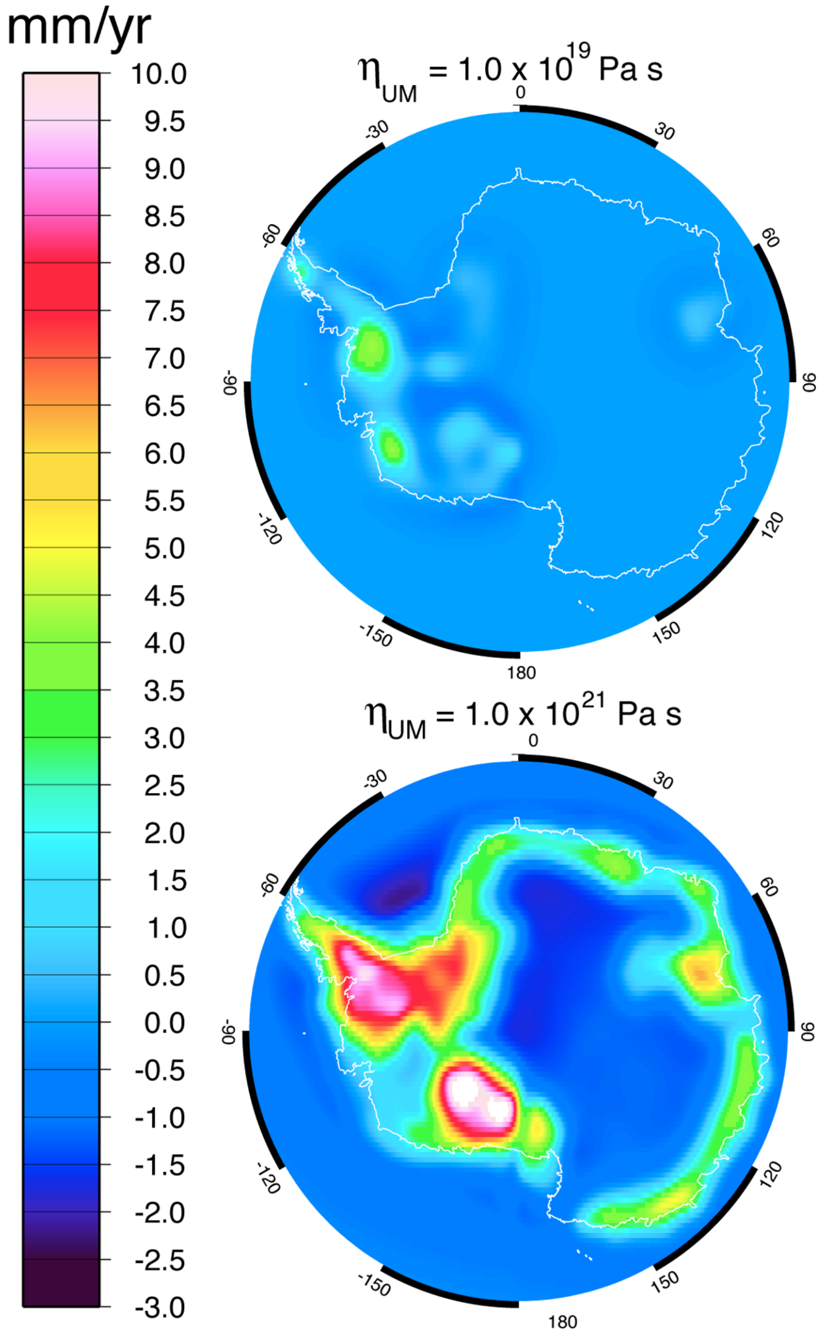
Ice loss and sea-level rise

- Probable sea-level rise by 2100: 28-43 cm * (IPCC, 2007)
- Probable sea-level rise by 2100: 26-98 cm * (IPCC, 2013)

* Does not include effects of ice-sheet dynamical changes.

* "Confidence in projections of global mean sea level rise has increased ... inclusion of ice-sheet dynamical changes."

Glacial Isostatic Adjustment Depends on Earth Structure



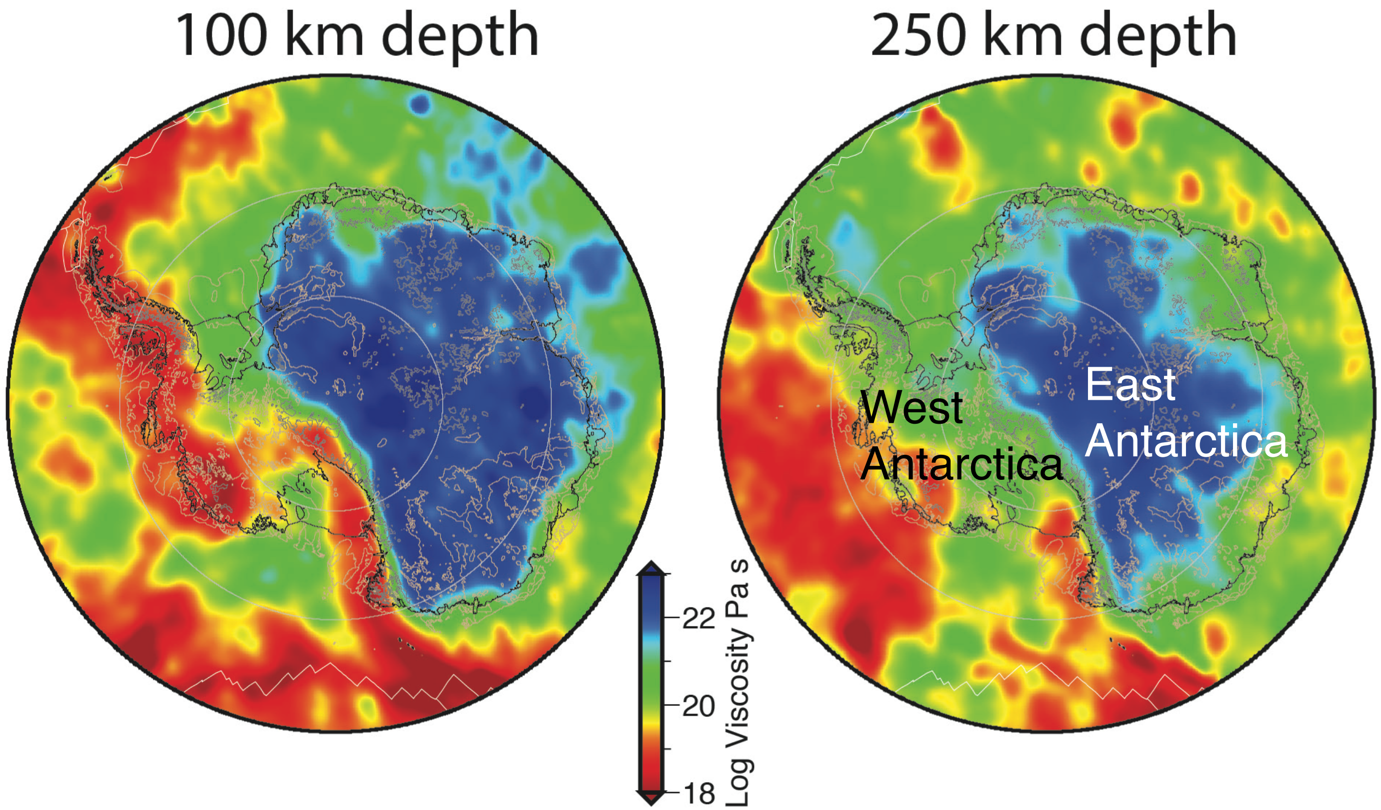
Low viscosity:
short-term memory
Sensitive only to Holocene

Computed GIA Uplift Rate for
Different Mantle Viscosities
(Ivins & James, 2005)

High Viscosity:
long-term memory
Sensitive to LGM

(courtesy D. Wiens)

Estimated Mantle Viscosity Maps



isotropic shear velocity (Lloyd et al., in prep) --> viscosity estimate
method of Wu et al., 2012, and relationships from experimental rock mechanics

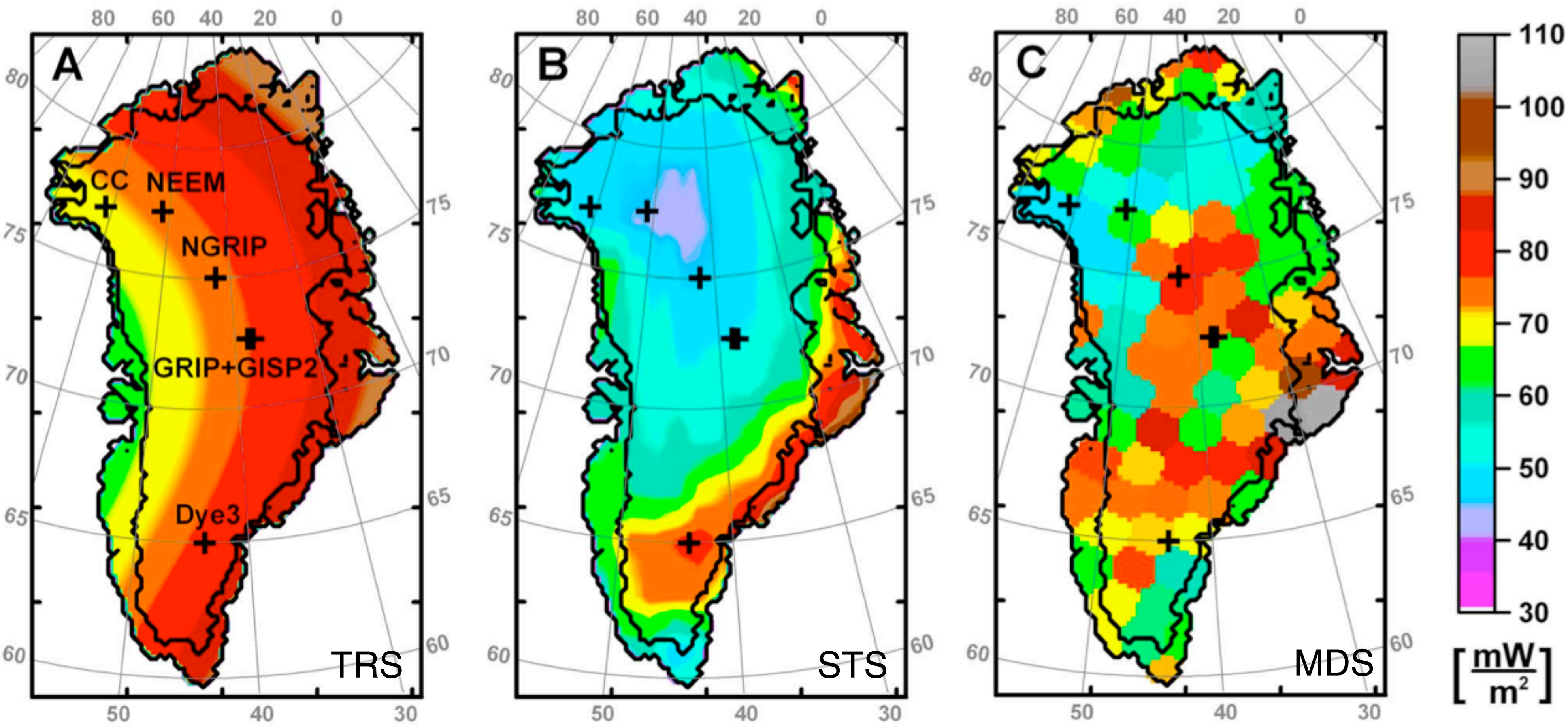
Very low viscosity (~ 10^{18} – 10^{19} Pa s) in upper mantle beneath much of West Antarctica -- GIA should occur over time periods of less than 500 years!

(courtesy D. Wiens)

Ice-sheet evolution depends on basal heat flux

Heat-flux models for Greenland

(Rogozhina et al., 2012)

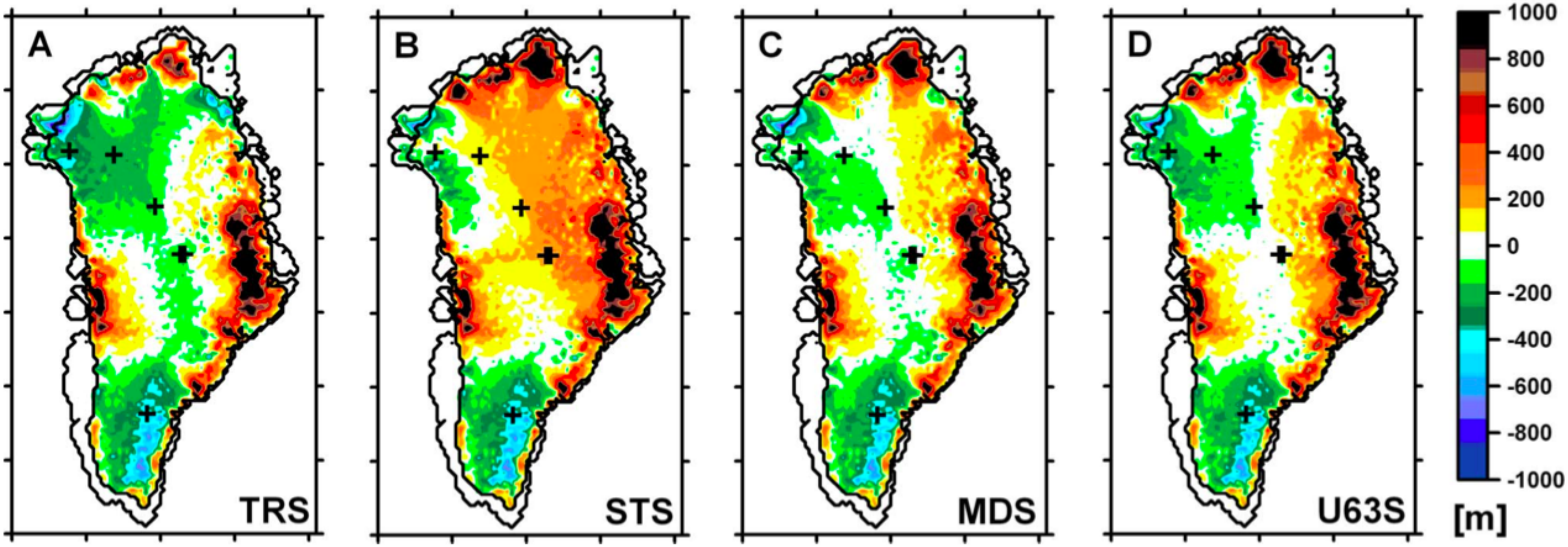


Pollack et al., 1993

Shapiro and Ritzwoller, 2004

Fox Maule et al., 2009

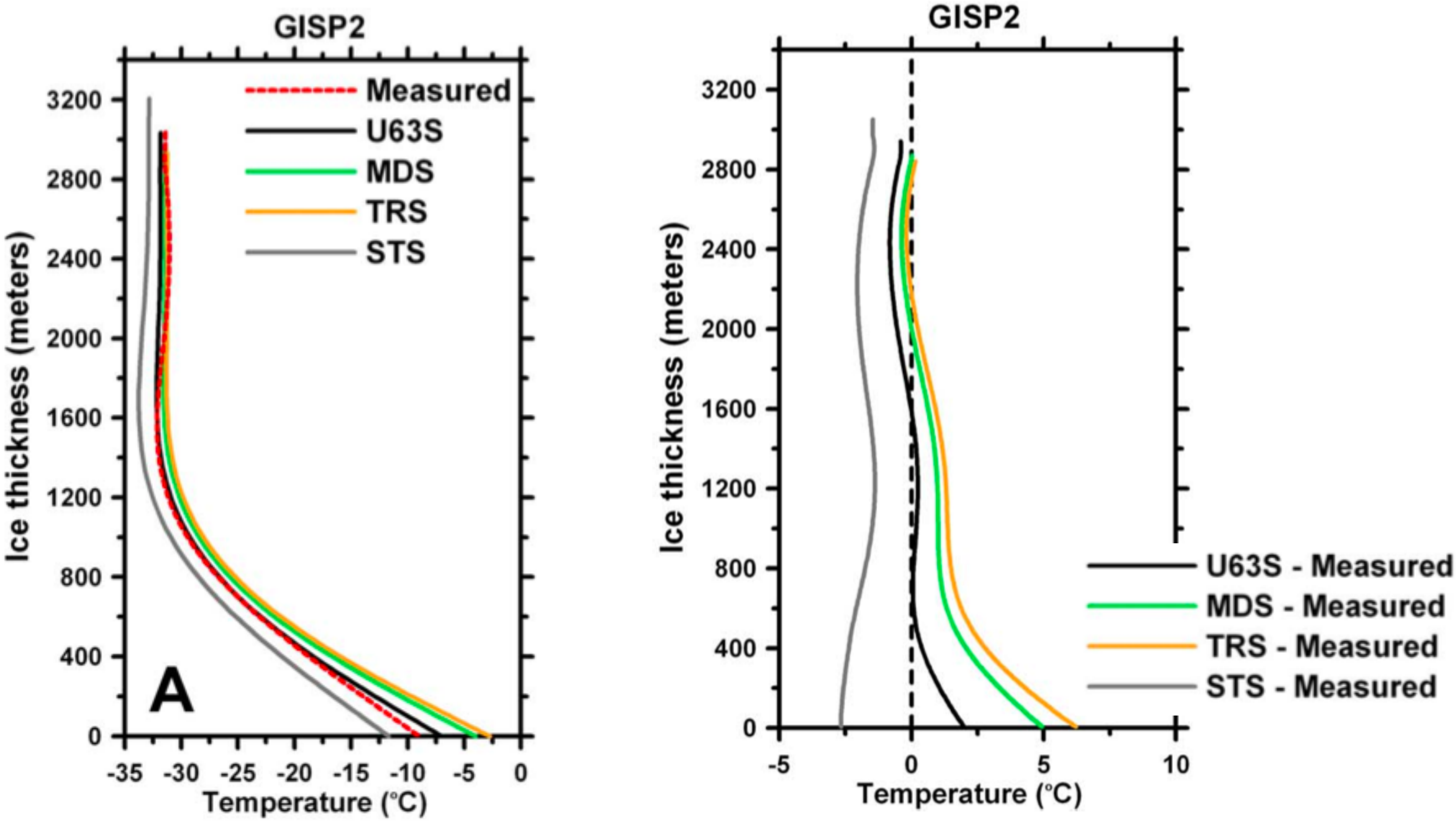
Predicted modern-day ice thickness
(predicted minus observed)



(Pollack) | (Shapiro and Ritzwoller) | (Fox Maule) | constant 63 mW/m²

(Rogozhina et al., 2012)

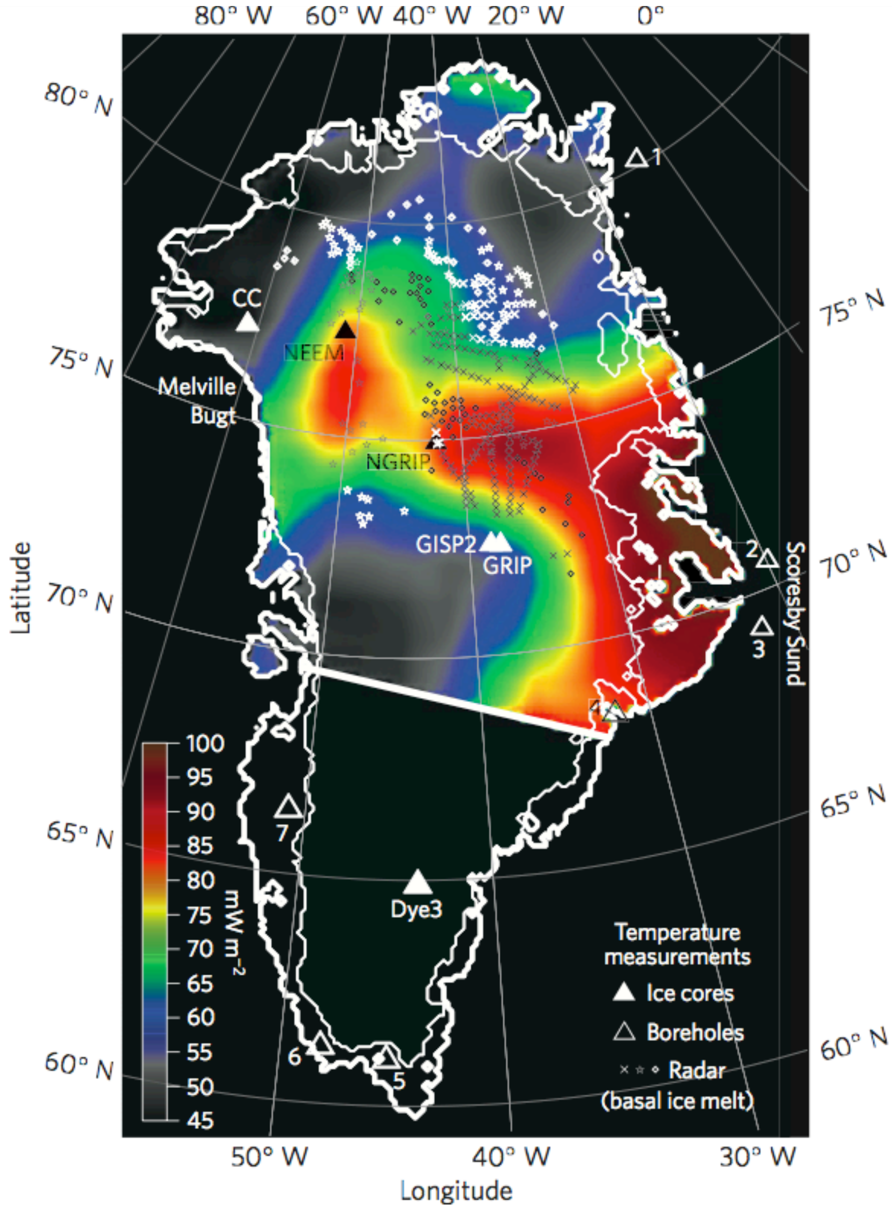
Predicted temperature profile in ice, and residual



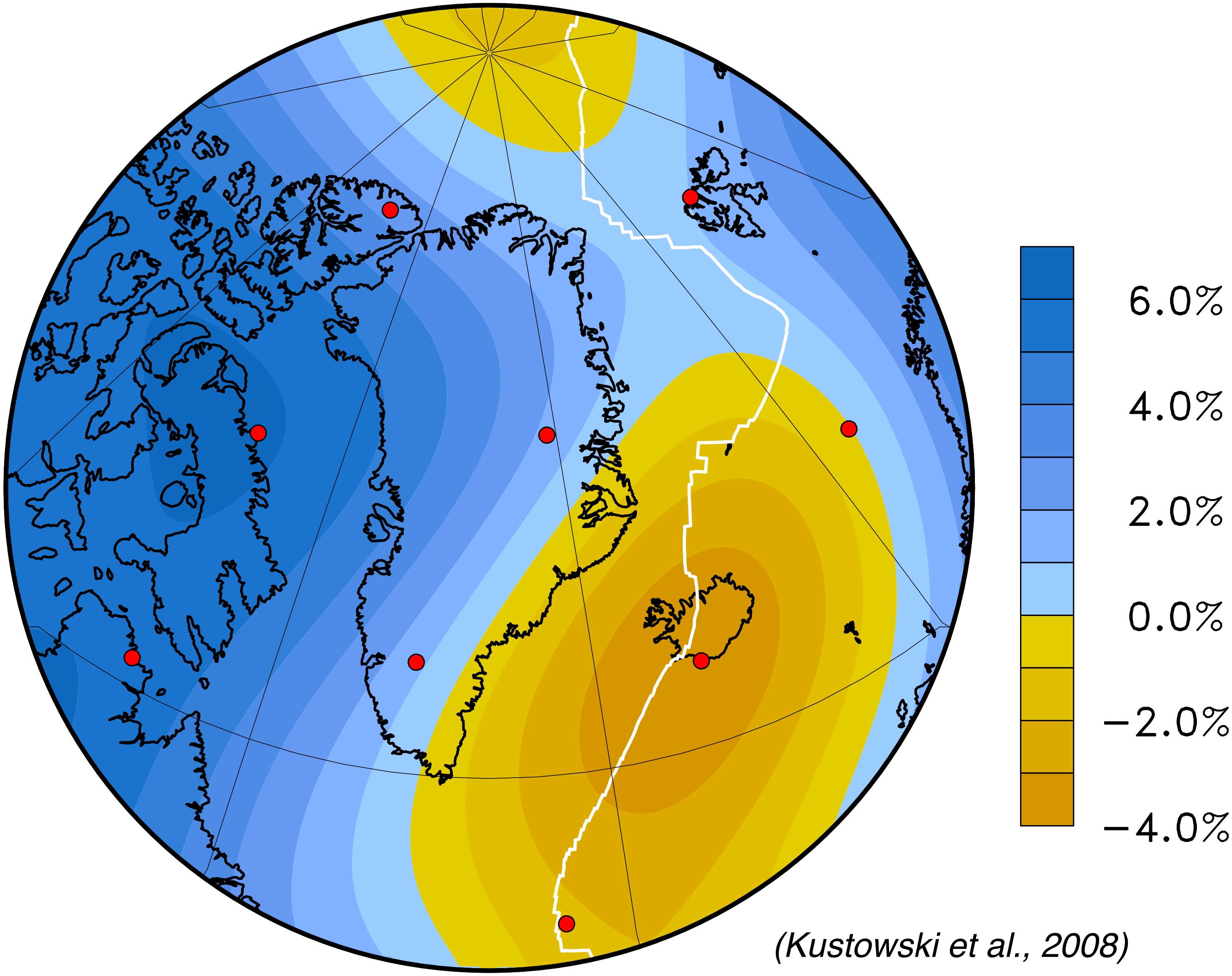
(Rogozhina et al., 2012)

Heat-flux models for Greenland

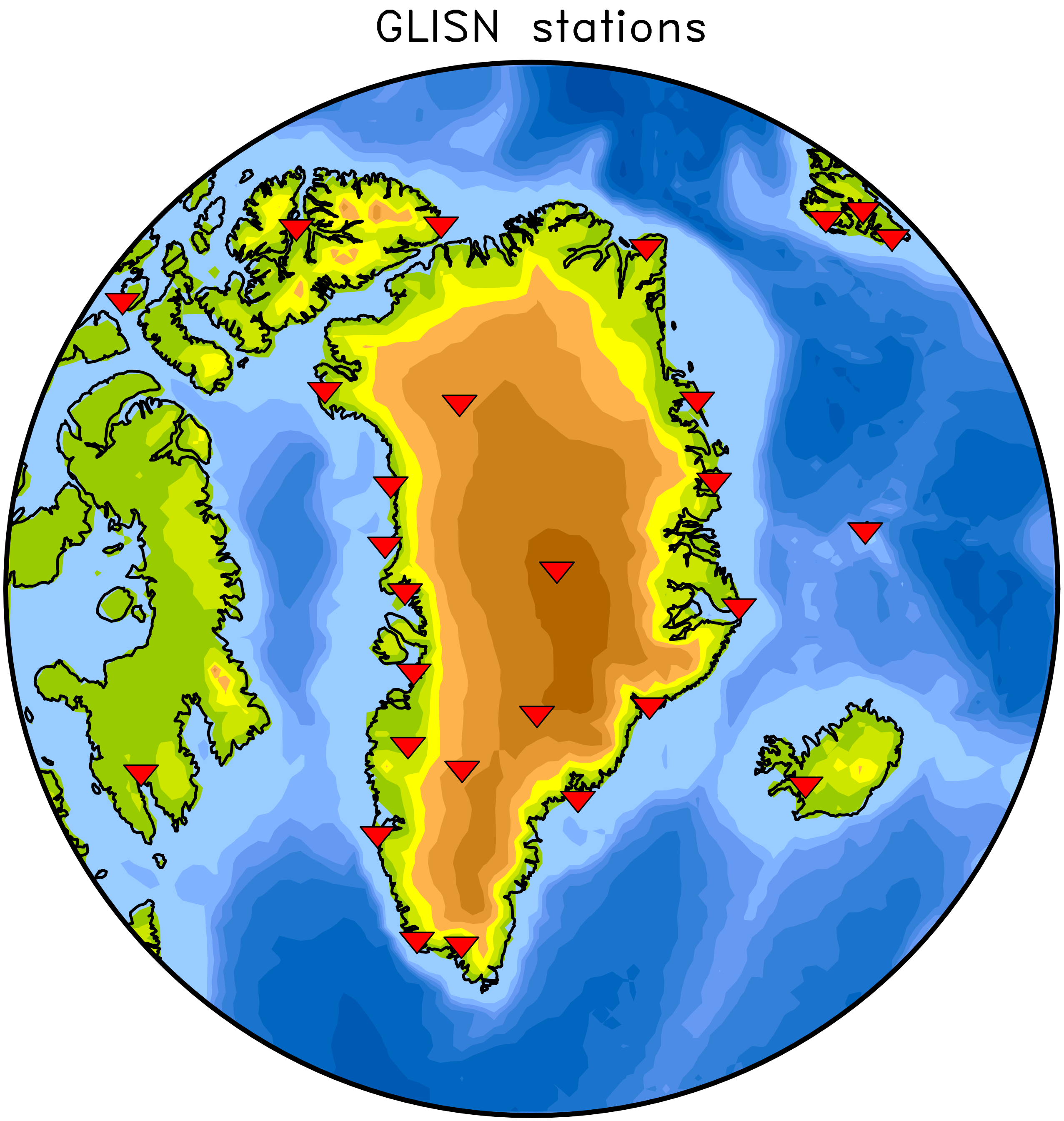
(Rogozhina et al., 2016)



Global seismic-tomography models: resolving wavelength ≈ size of Greenland

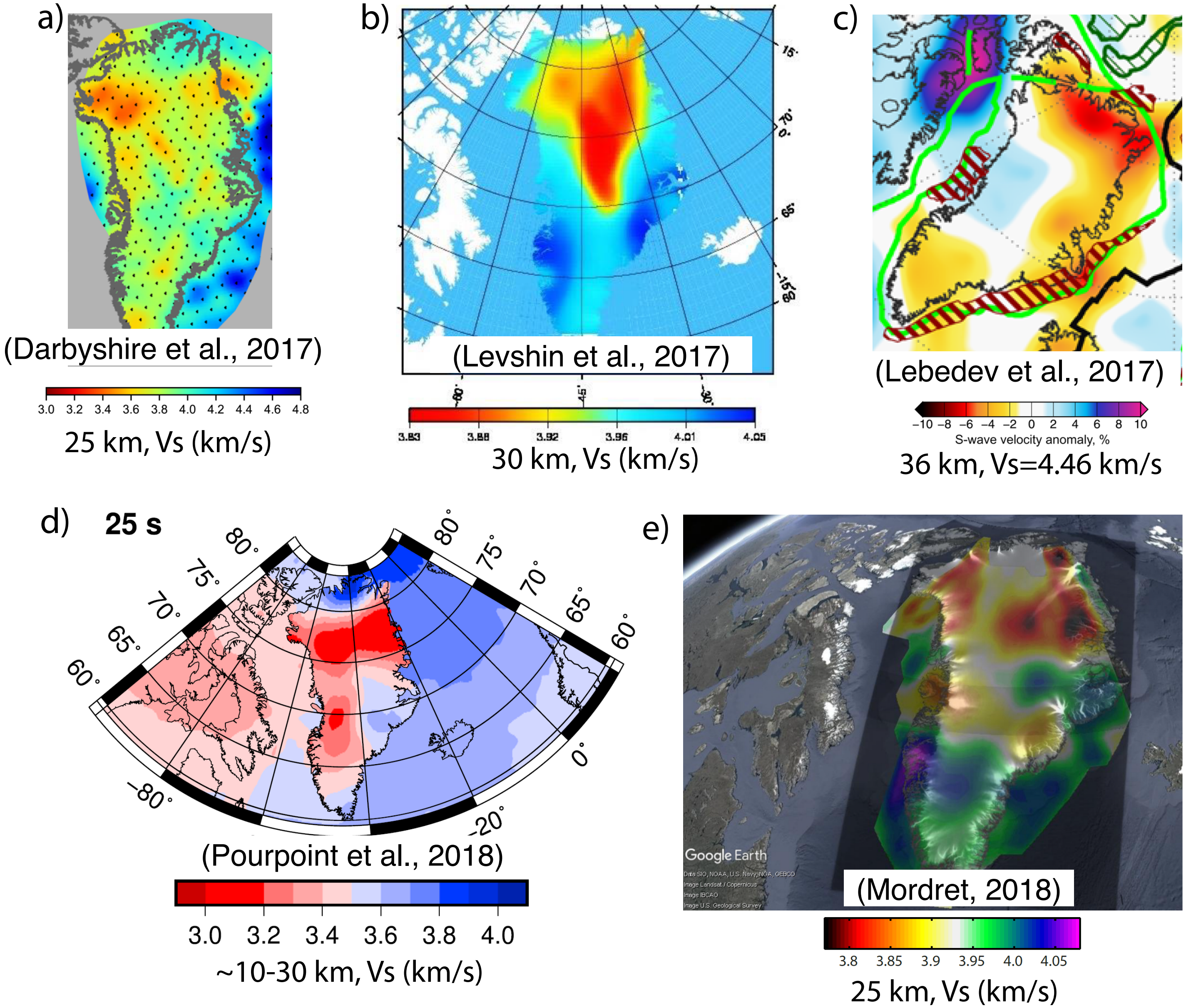


(Kustowski et al., 2008)



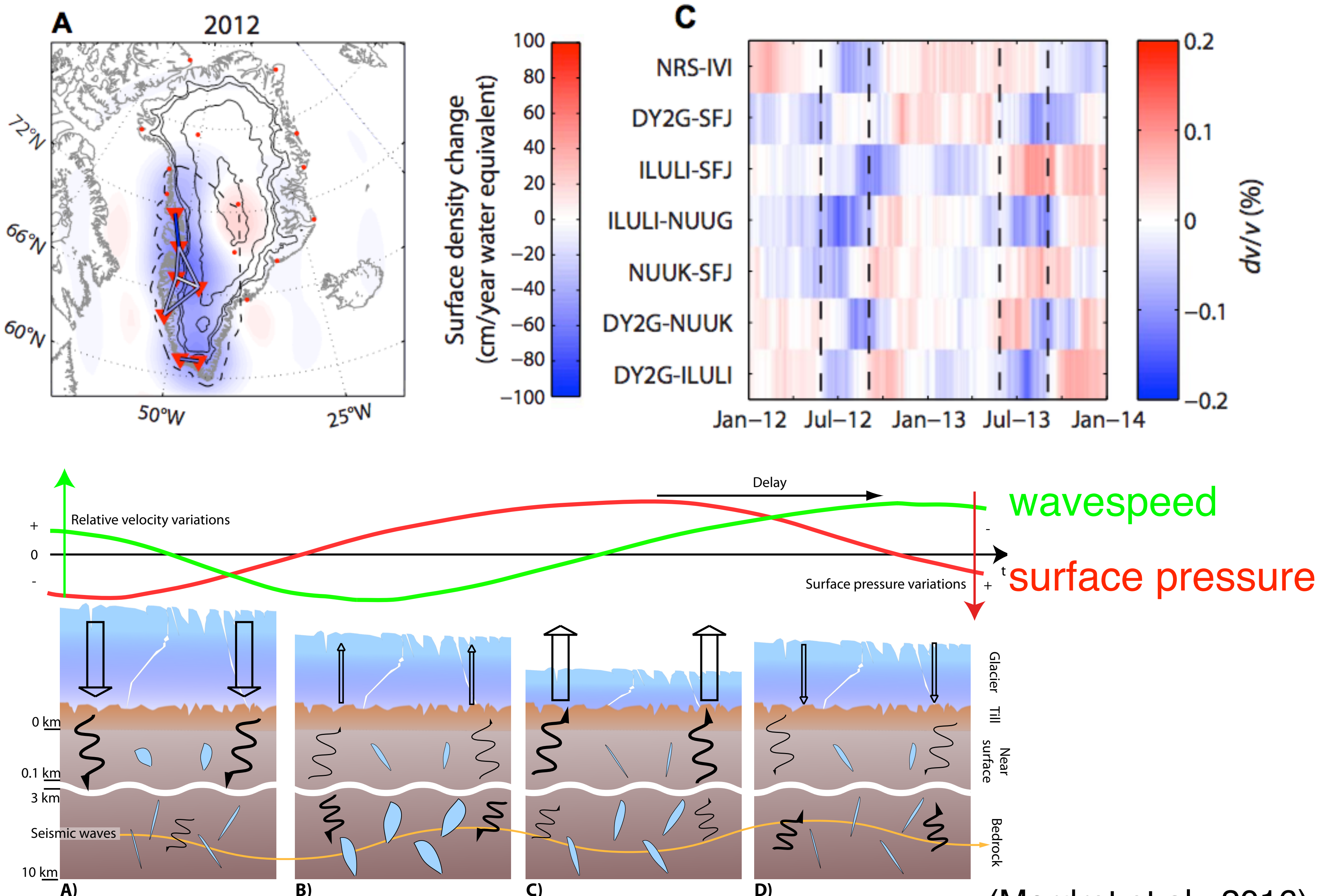
International, cooperative effort

Recent S-velocity models for Greenland at crustal depths



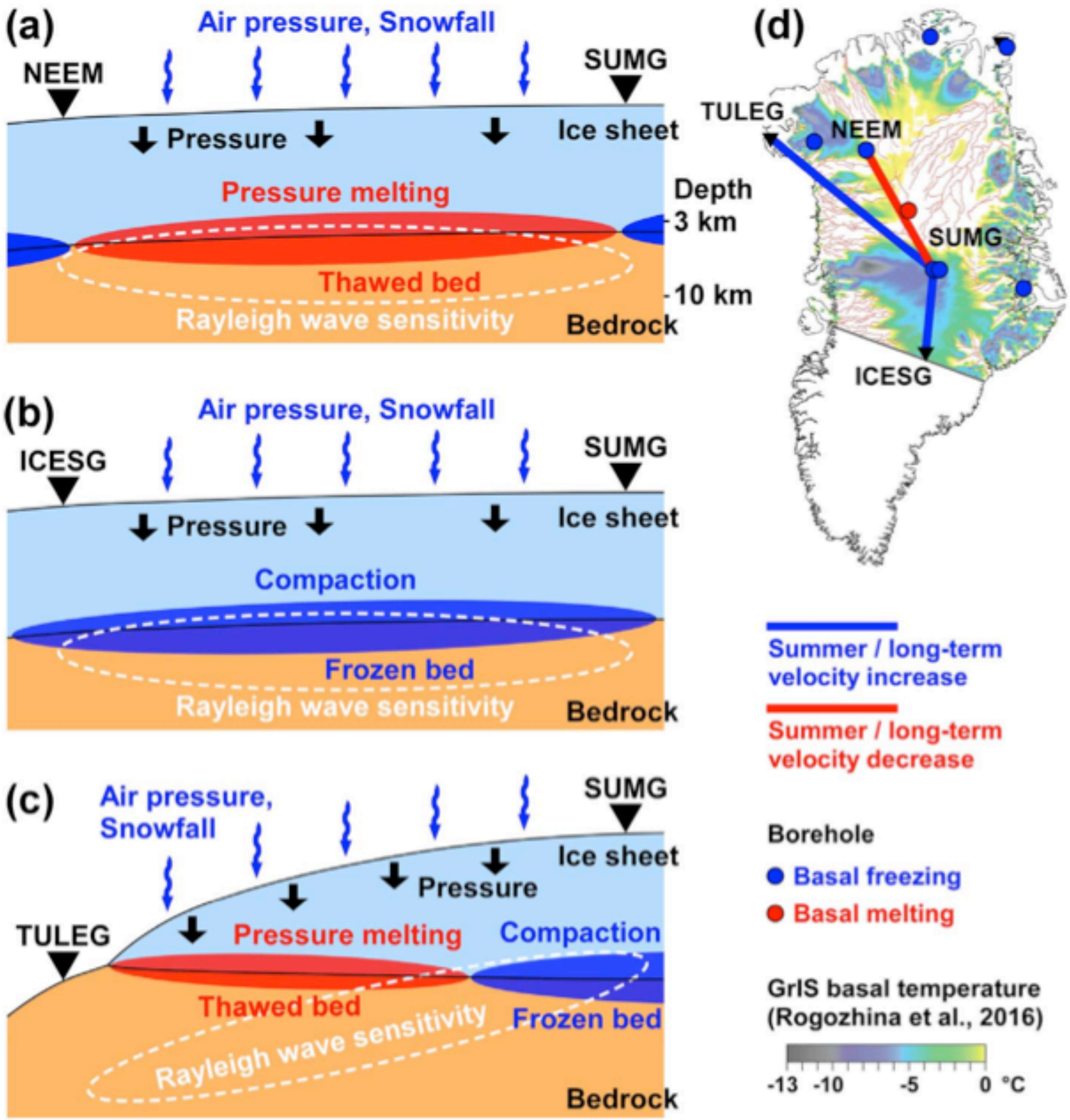
(compiled by A. Mordret)

Ice-bed interface: time-varying seismic wave speeds



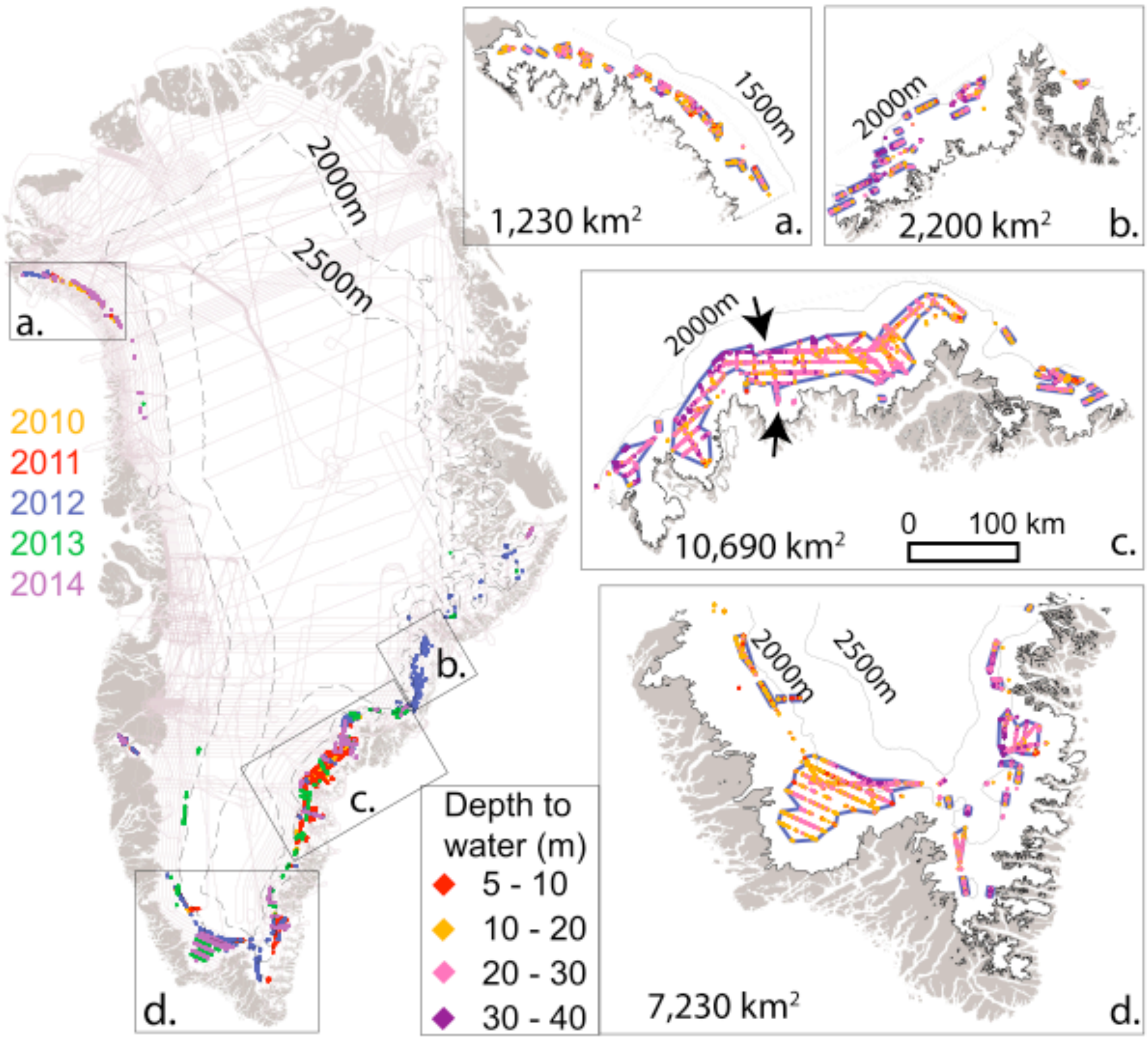
(Mordret et al., 2016)

Ice-bed interface: time-varying seismic wave speeds



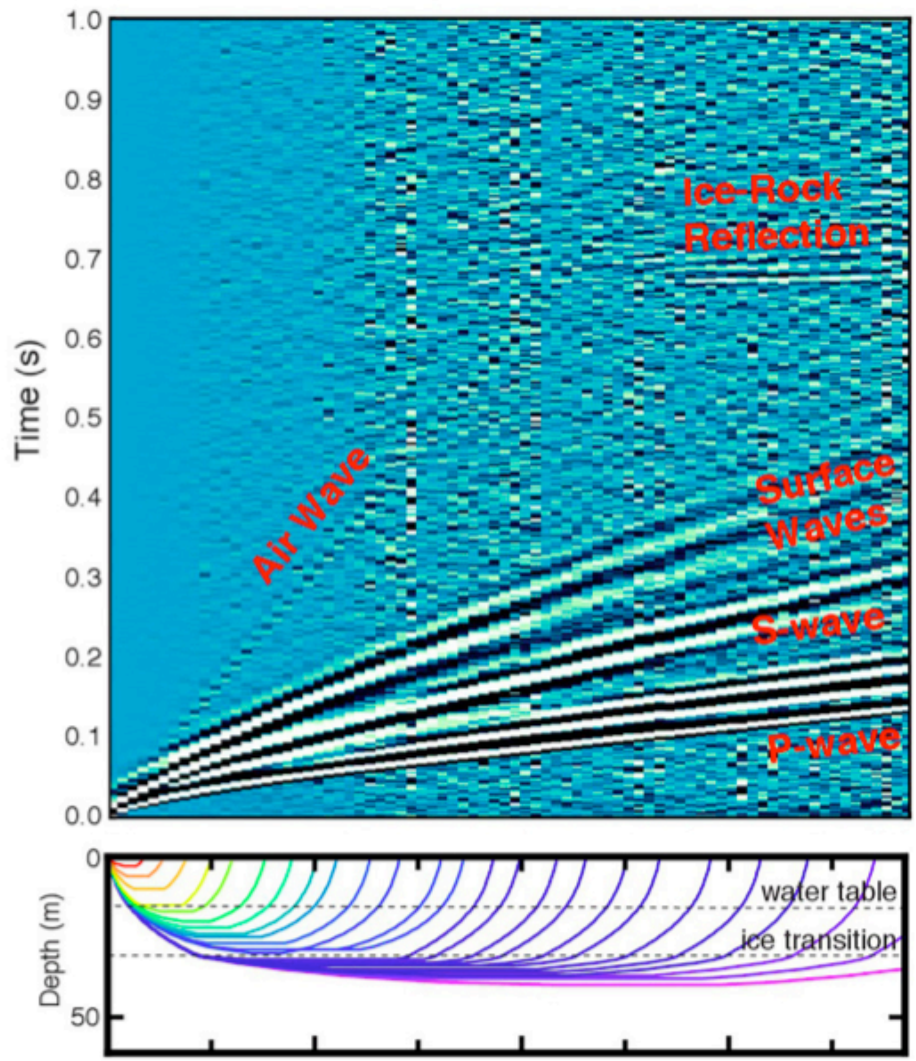
(Toyokuni et al., 2018)

Firn aquifers in Greenland: storage and discharge of liquid water!

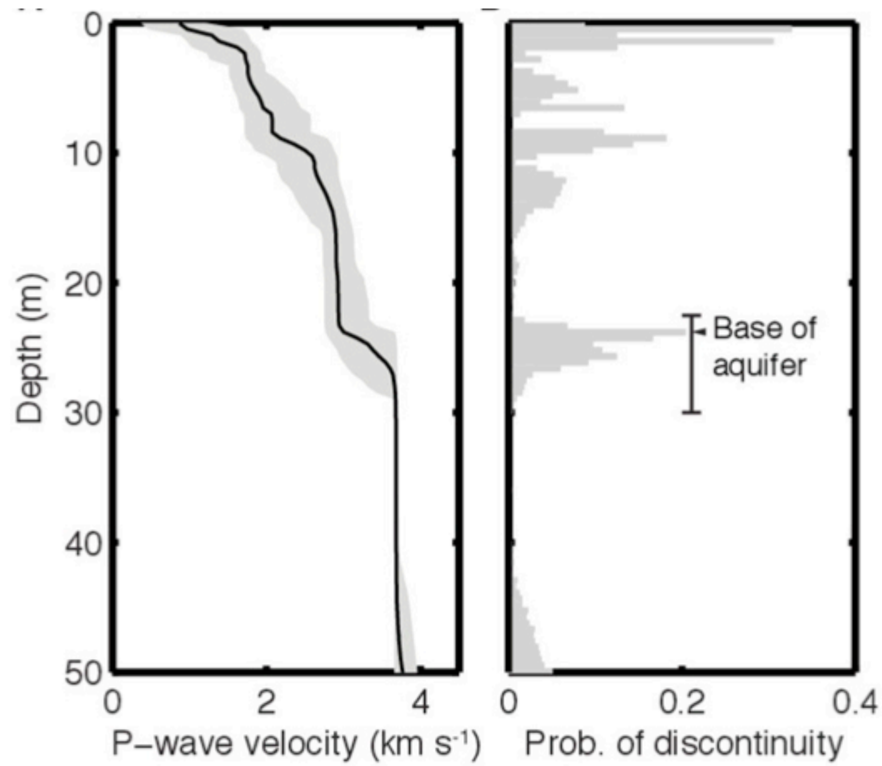


(Miège et al., 2016)

Surface mapped by radar; base by seismic refraction



(Montgomery et al., 2017)



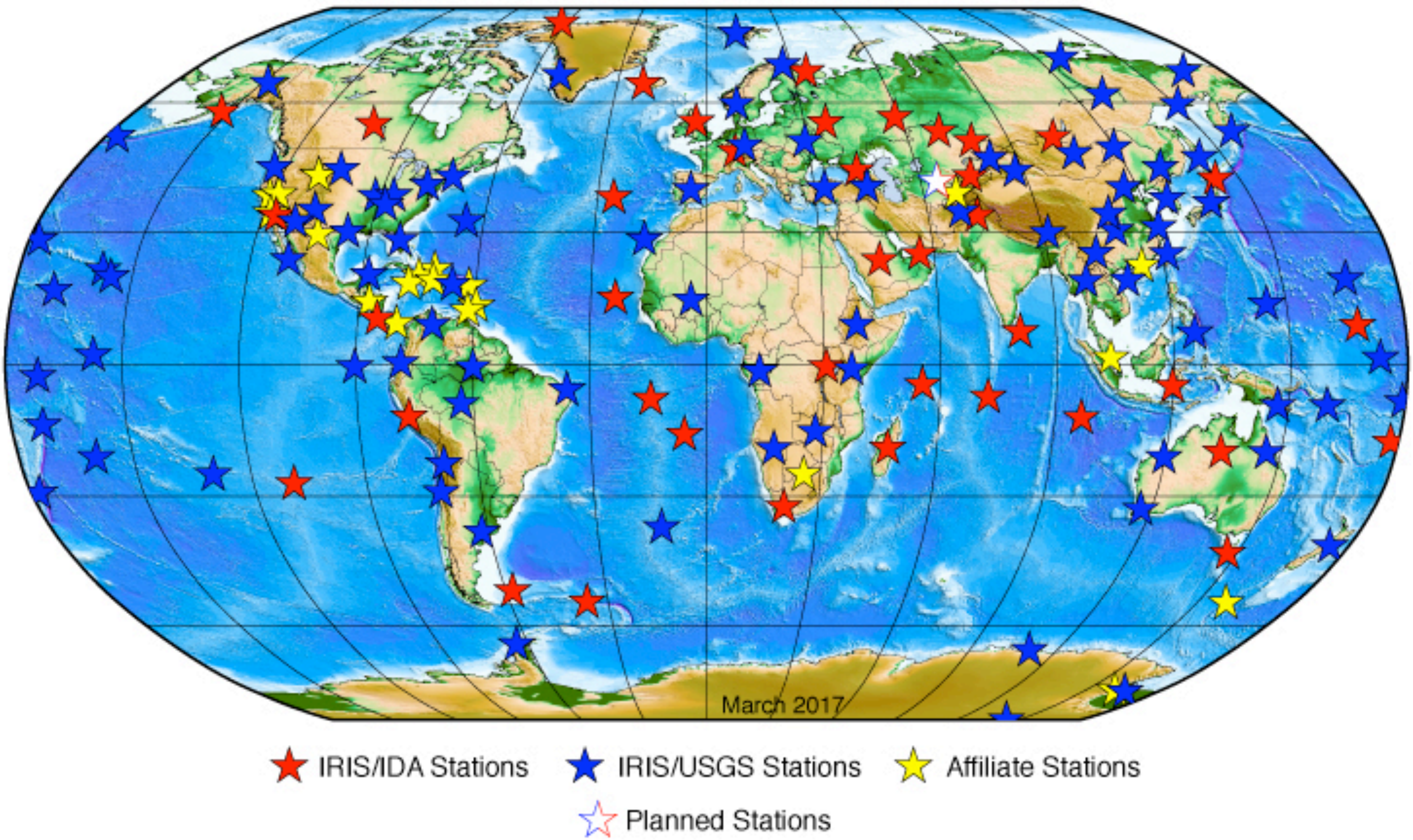
Probable (but unknown!) effect on ice dynamics

Ice loss and sea-level rise

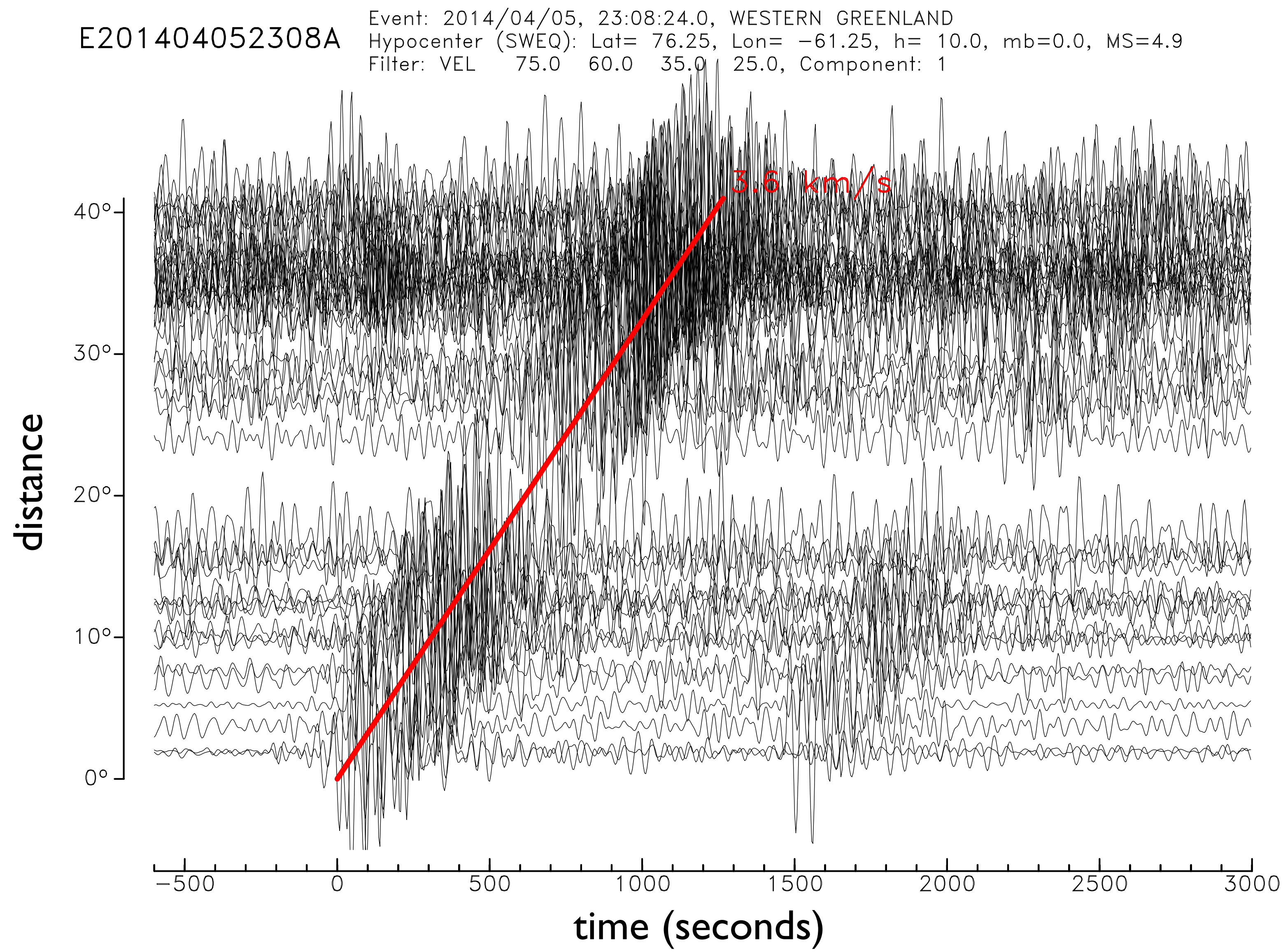
- Probable sea-level rise by 2100: 28-43 cm (IPCC, 2007)
- Probable sea-level rise by 2100: 26-98 cm (IPCC, 2013)

About half of net mass loss in Greenland is “dynamic” (calving).
...
And ~20% of the dynamic loss is observed on GSN stations...

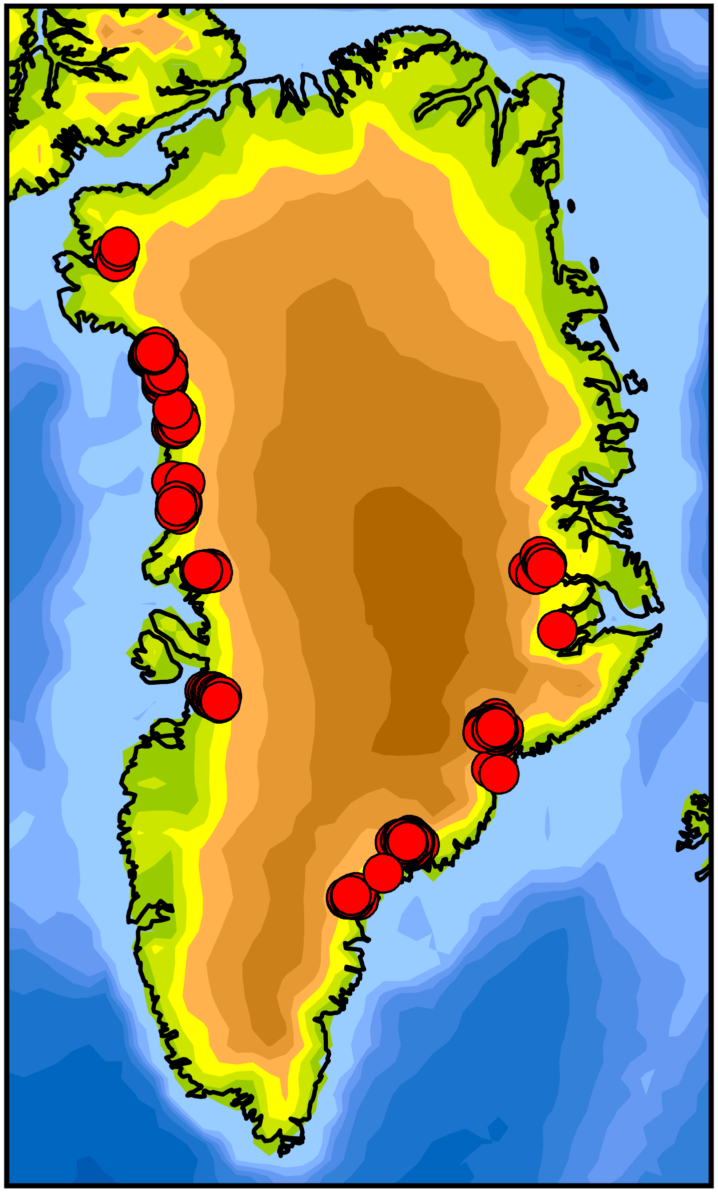
Global Seismographic Network



Greenland earthquake:
Seismograms from Global Seismographic Network

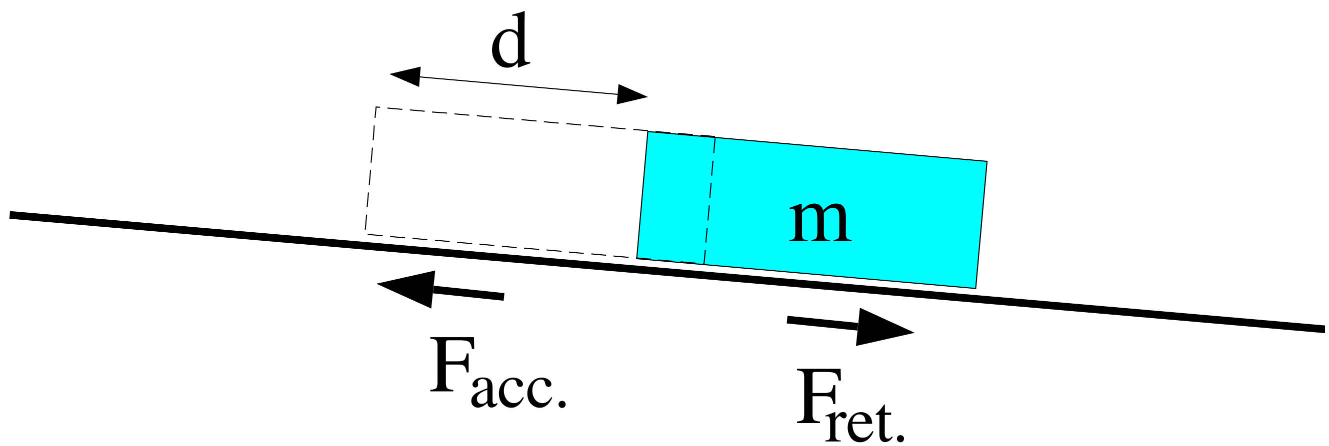


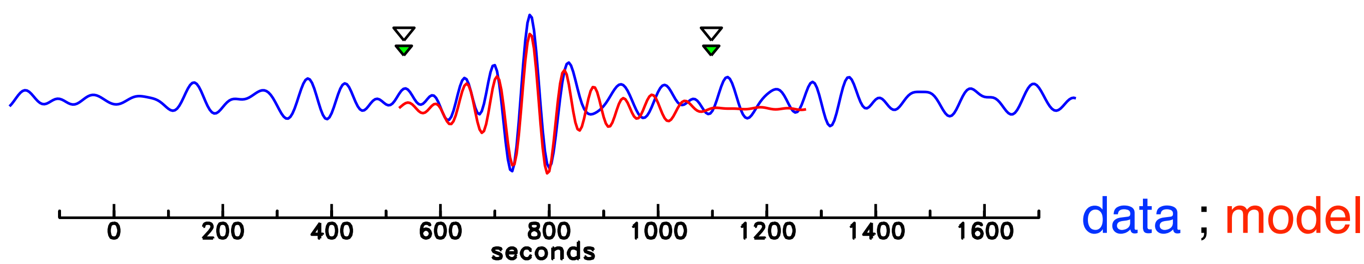
Glacial earthquakes in Greenland



(updated from Nettles and Ekström, 2010)

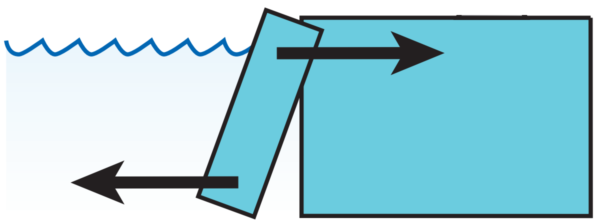
Momentum-transfer ("landslide") force model

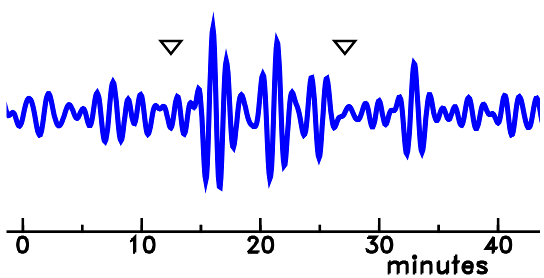


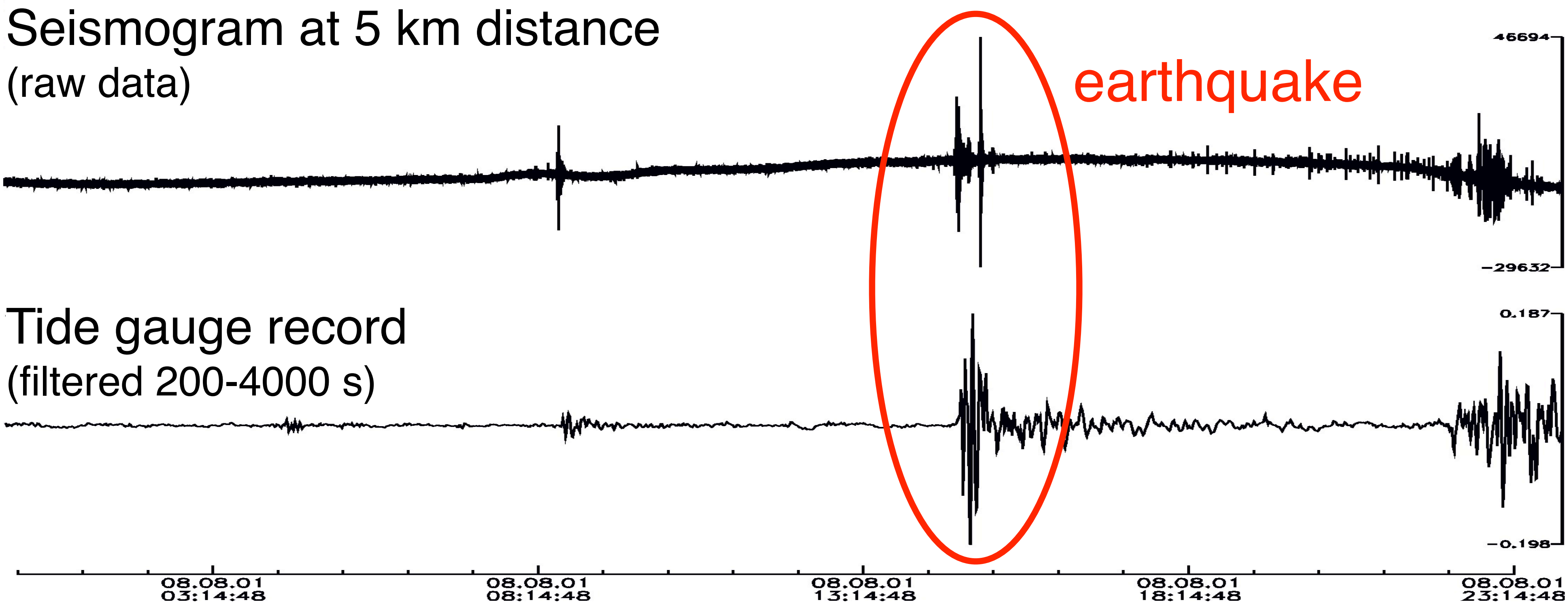


(Ekström et al., 2003; Tsai and Ekström, 2007; Nettles and Ekström, 2010; Veitch and Nettles, 2012; Walter et al., 2012; Sergeant et al., 2016; Olsen and Nettles, 2017)

Seismic signal is generated by reaction force on glacier face as iceberg capsizes

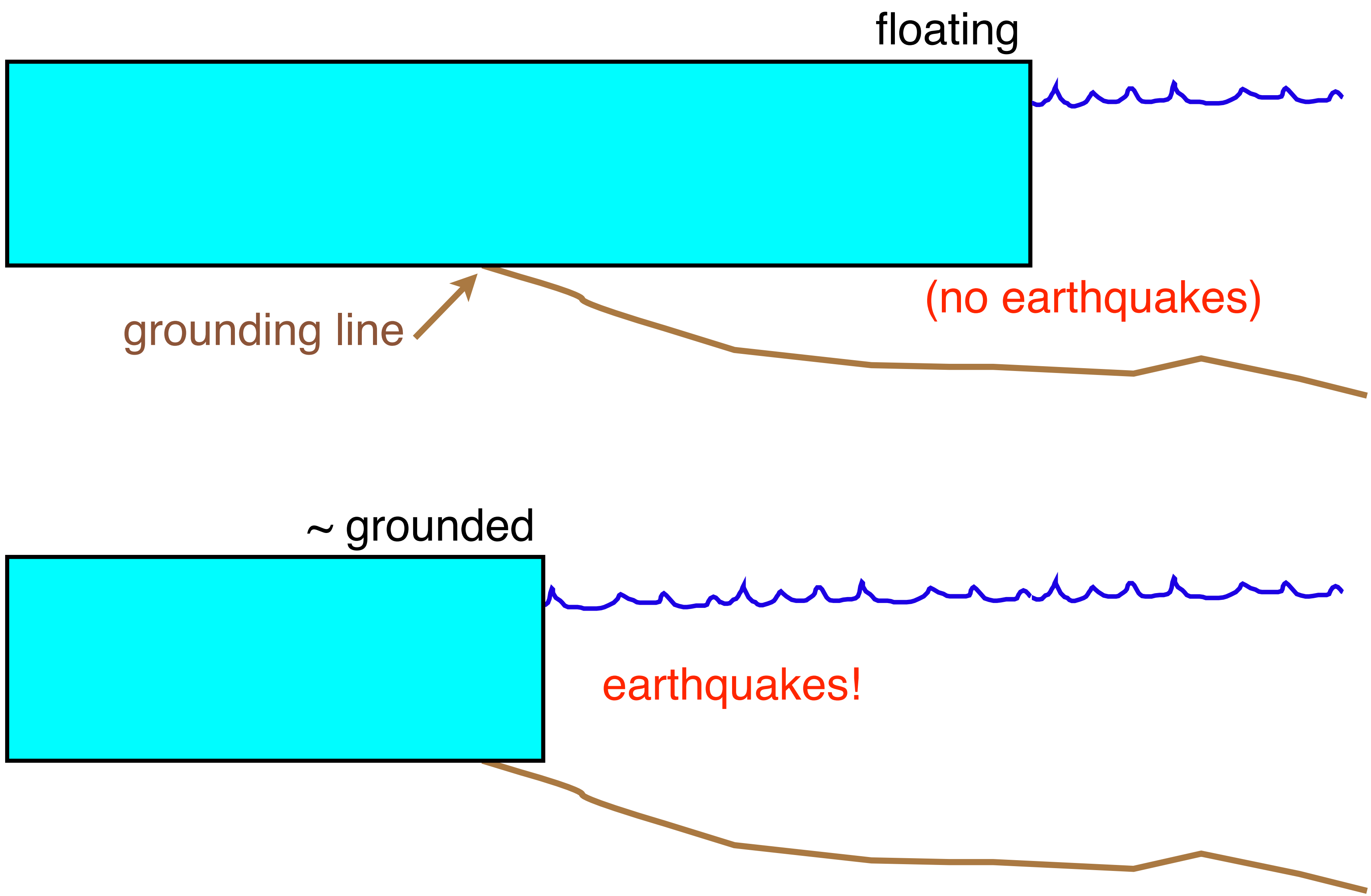




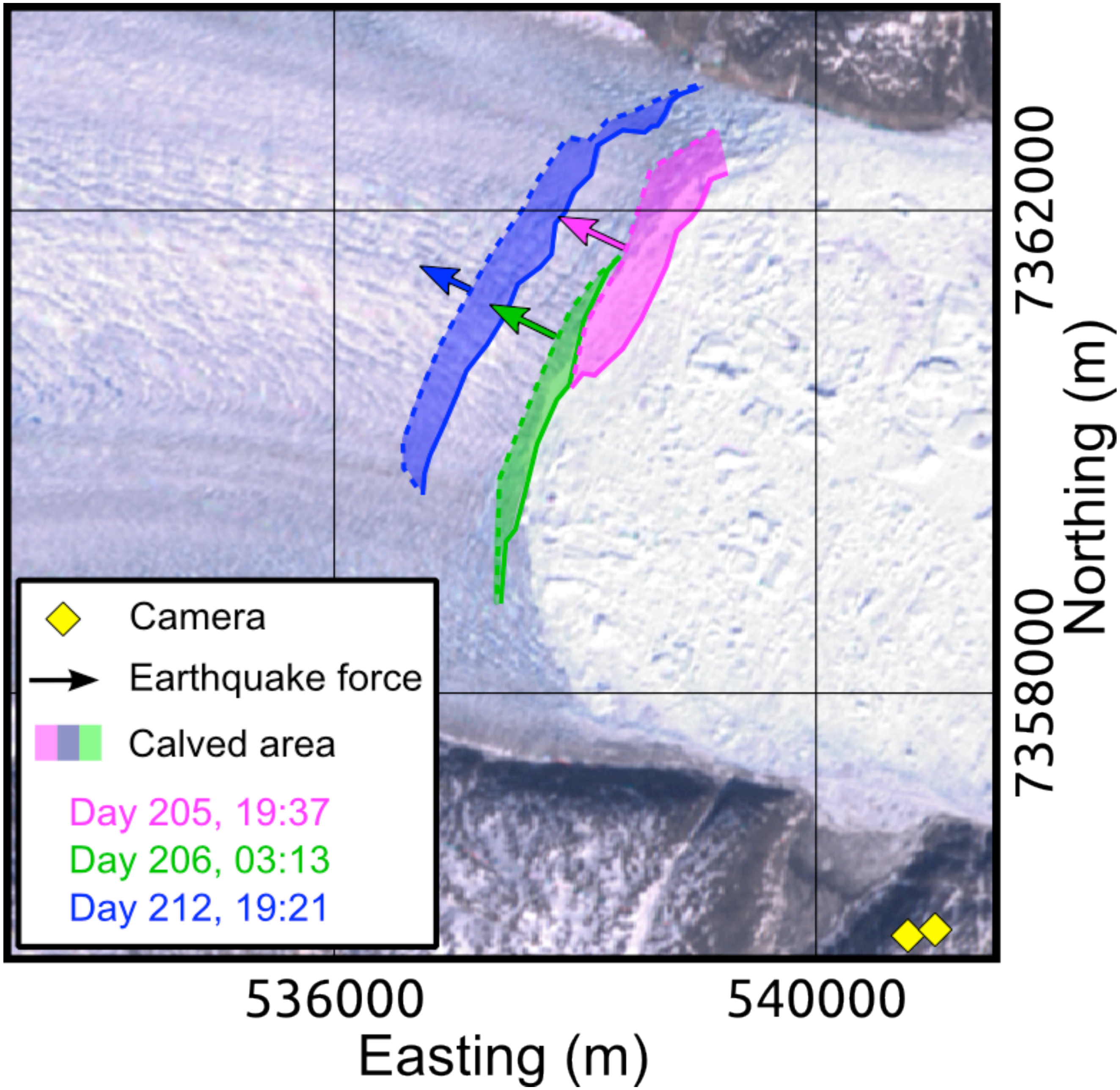


Seismogram at 5 km distance
(raw data)
earthquake
46694
-29632
Tide gauge record
(filtered 200-4000 s)
0.187
-0.198
08.08.01 03:14:48
08.08.01 08:14:48
08.08.01 13:14:48
08.08.01 18:14:48
08.08.01 23:14:48

Earthquakes occur when calving front is nearly grounded

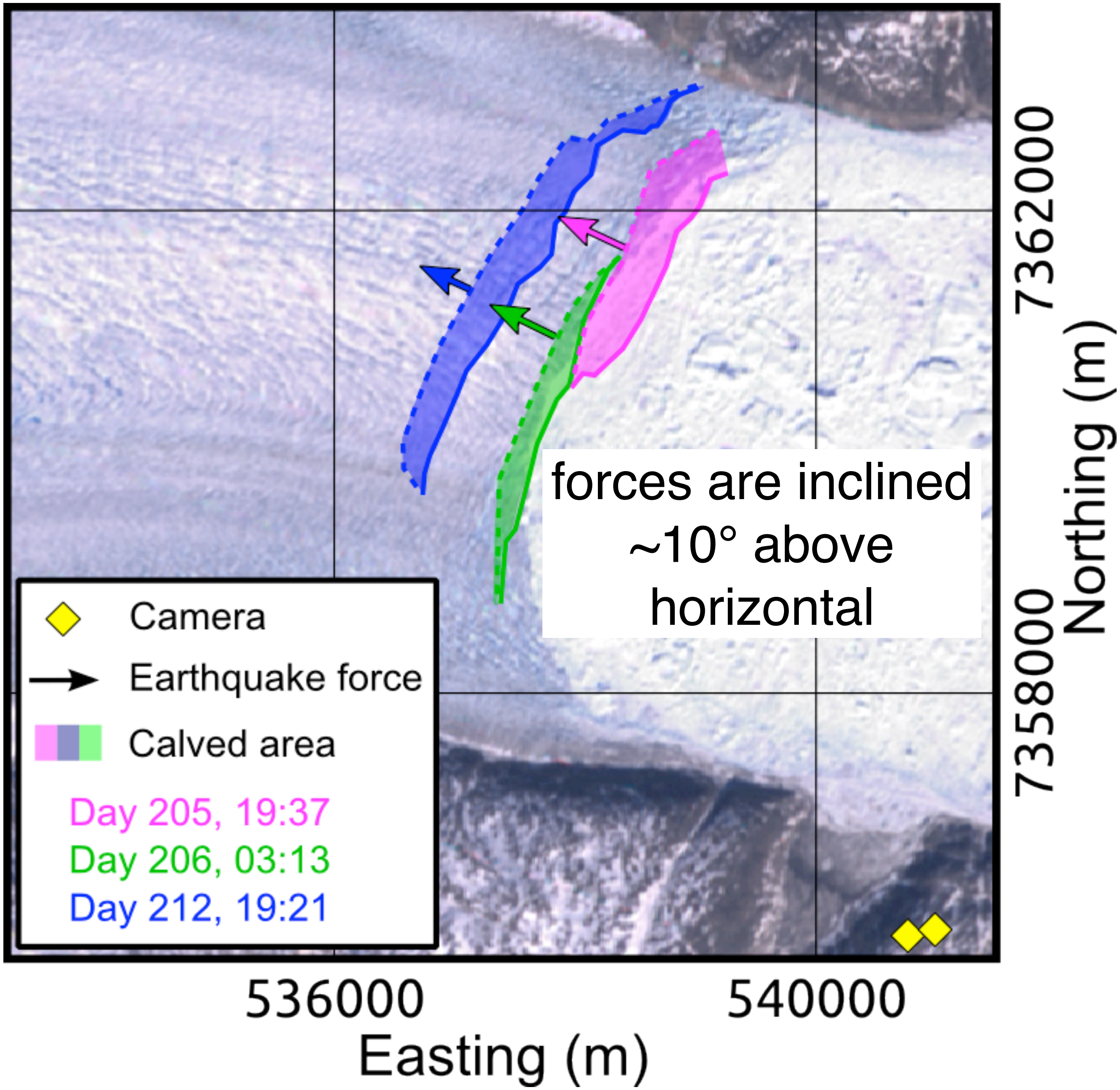


Forces in detail: geometry of calved blocks from stereo camera imagery



thanks toT. Murray, N. Selmes, T.D. James

Forces in detail: geometry of calved blocks from stereo camera imagery



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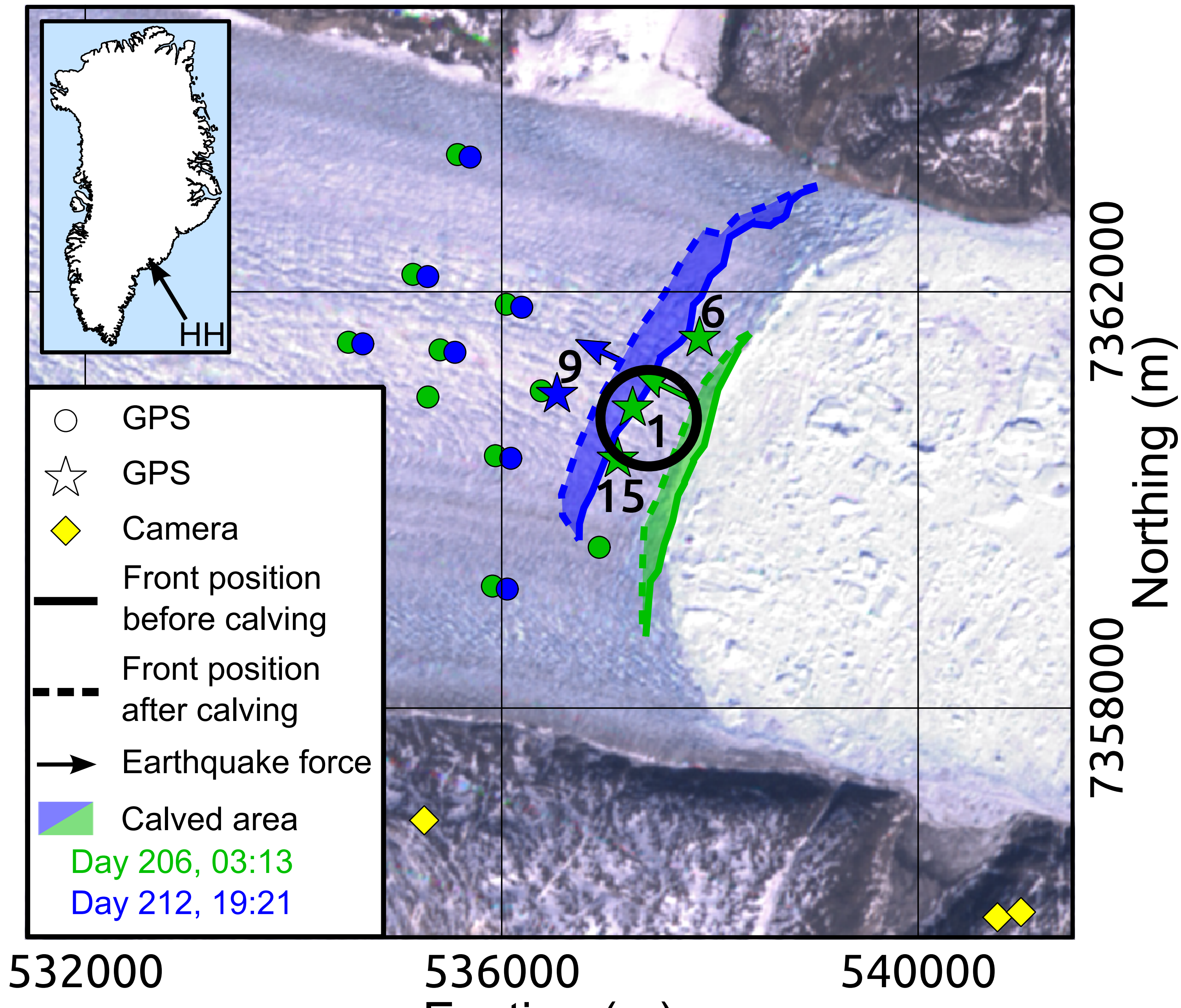
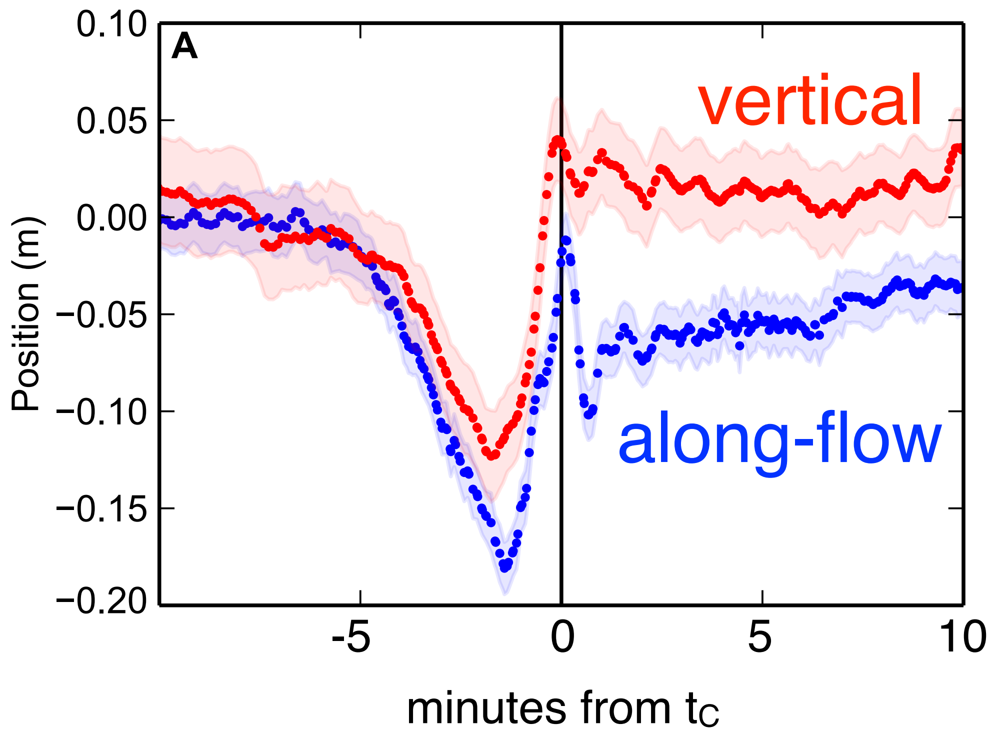
GPS receivers record glacier motion



(Murray et al., 2015)

GPS sensor 1, doy 206

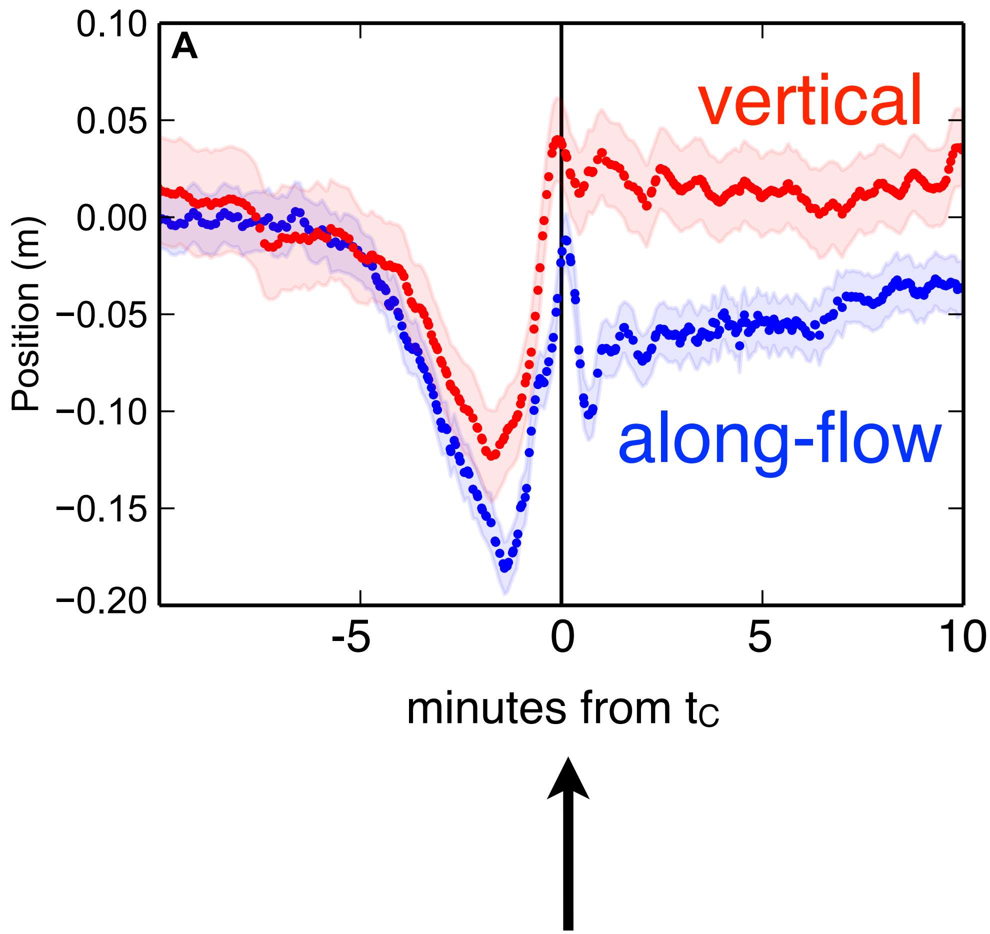


earthquake centroid time

glacier displacement direction *reverses* during earthquake

(Murray, Nettles et al., 2015)

GPS sensor 1, doy 206

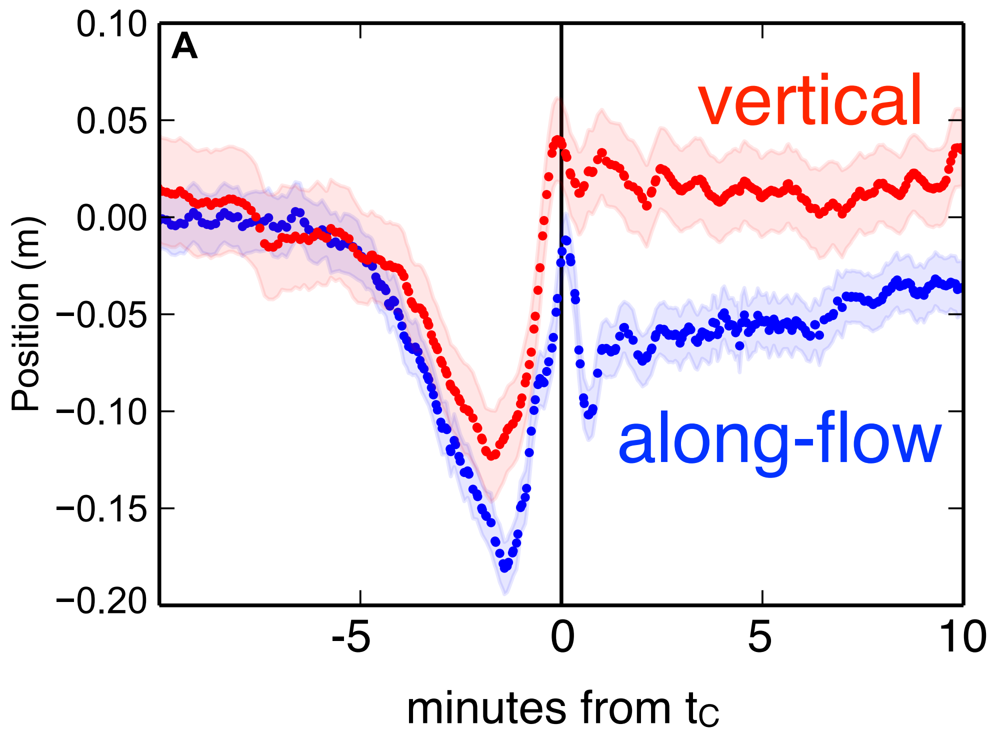


earthquake centroid time

glacier displacement direction *reverses* during earthquake, and terminus is drawn down

(Murray, Nettles et al., 2015)

GPS sensor 1, doy 206



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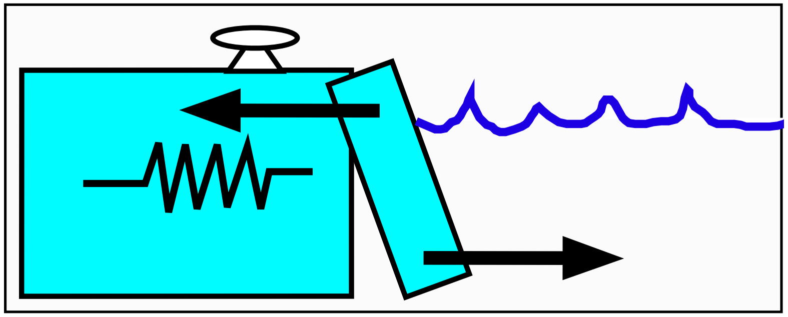
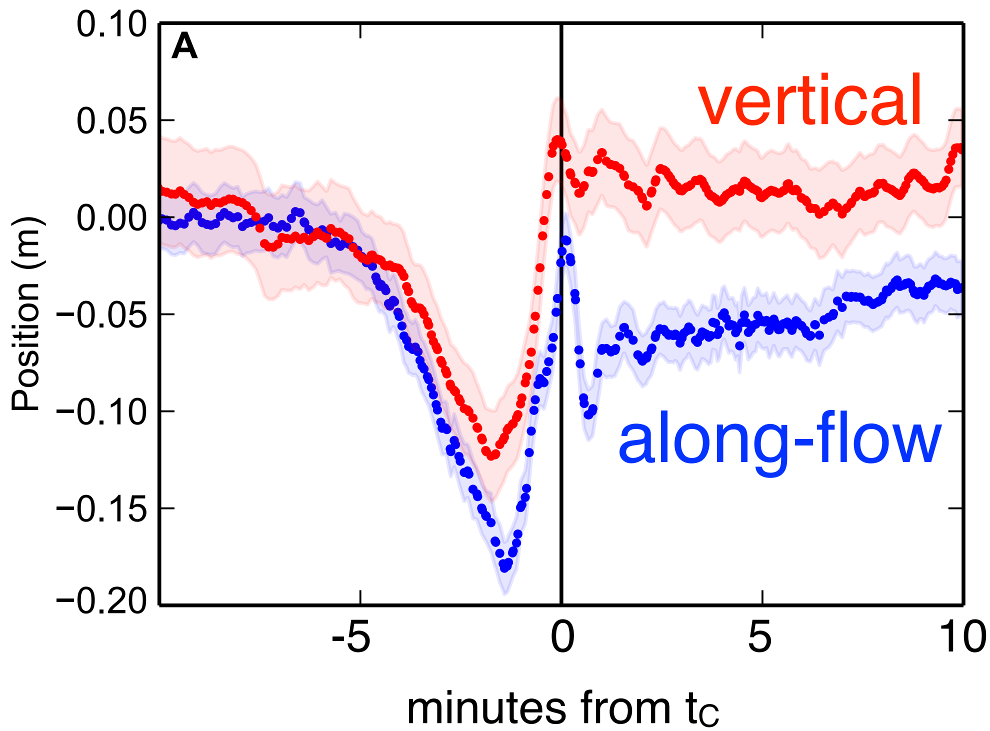


(Murray, Nettles et al., 2015)

GPS sensor 1, doy 206



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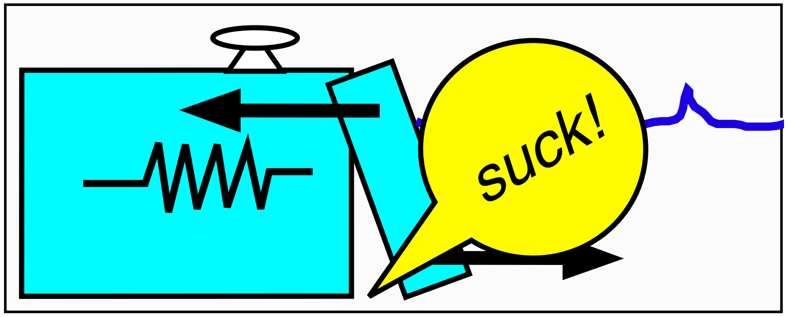
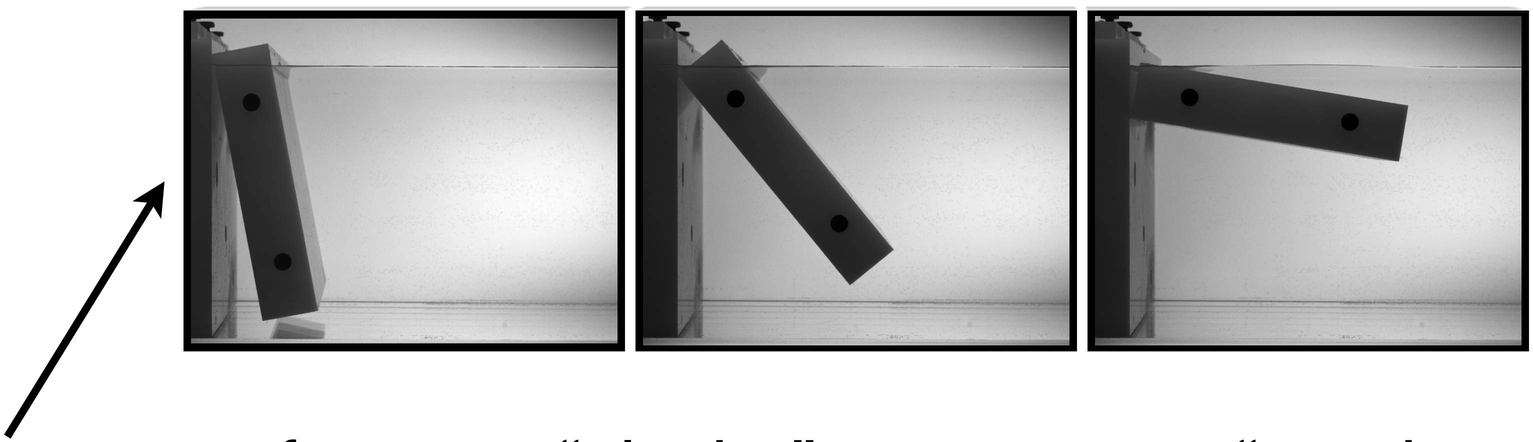


(Murray, Nettles et al., 2015)

Tank experiments:
plastic icebergs capsizing in water



measure force on “glacier”, pressure at “terminus”

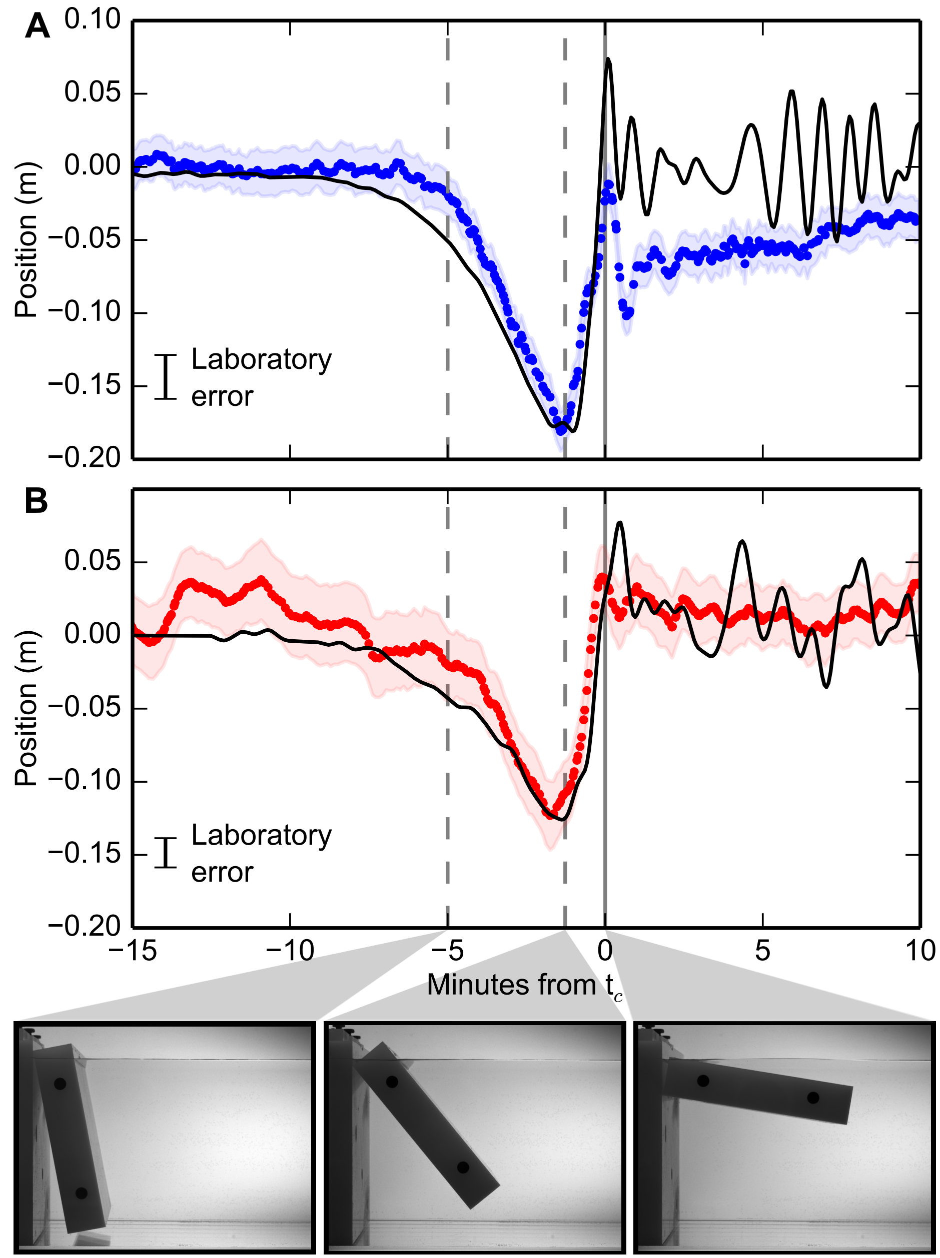
(Murray et al., 2015)

**Mac Cathles, Justin Burton*

Tank experiments: scaled results

elastic compression of glacier front

drawdown of terminus by dynamic pressure drop



GPS along-flow

GPS vertical

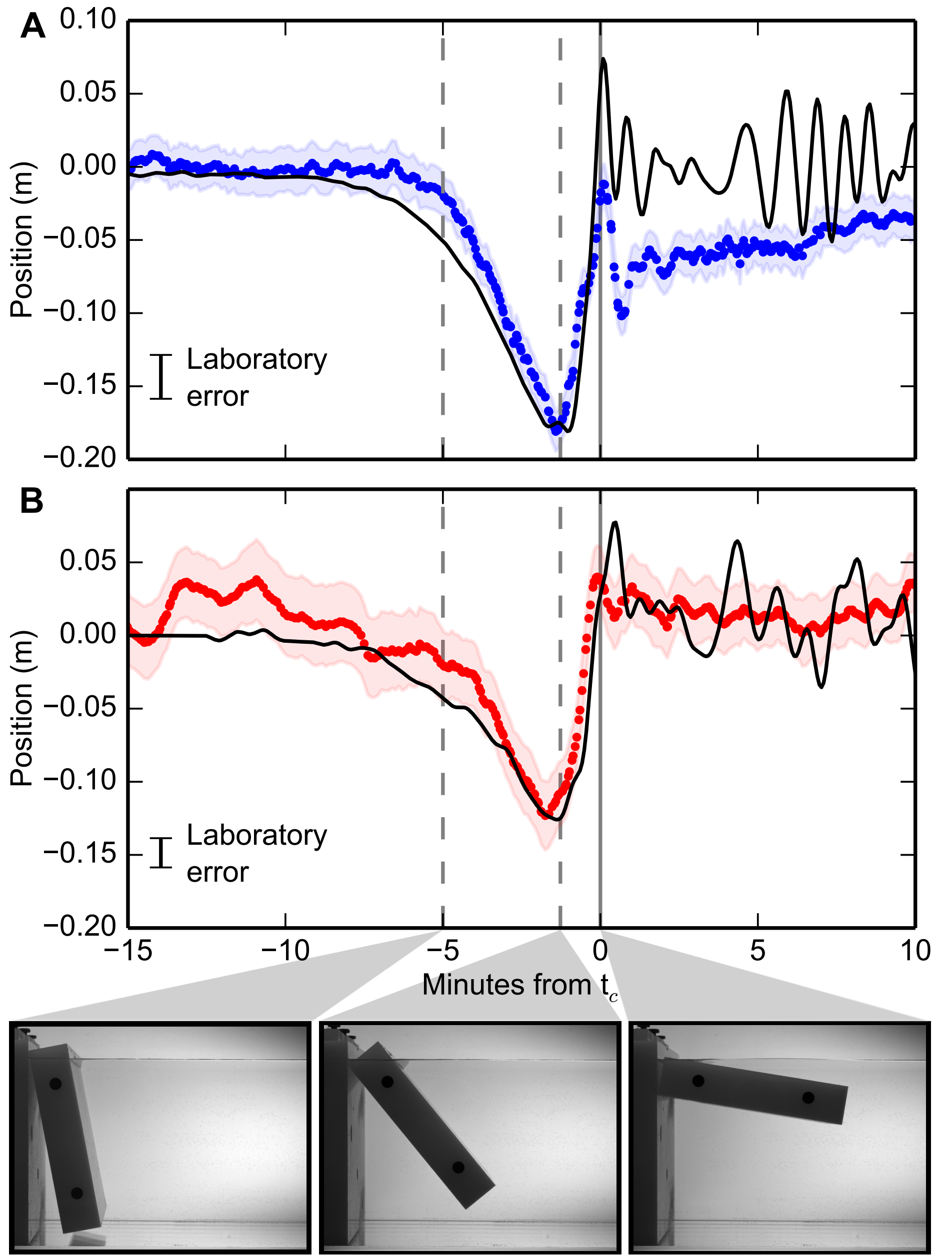
(Murray et al., 2015)

Tank experiments: scaled results

elastic compression of glacier front

drawdown of terminus by dynamic pressure drop

(force *up* on solid Earth)



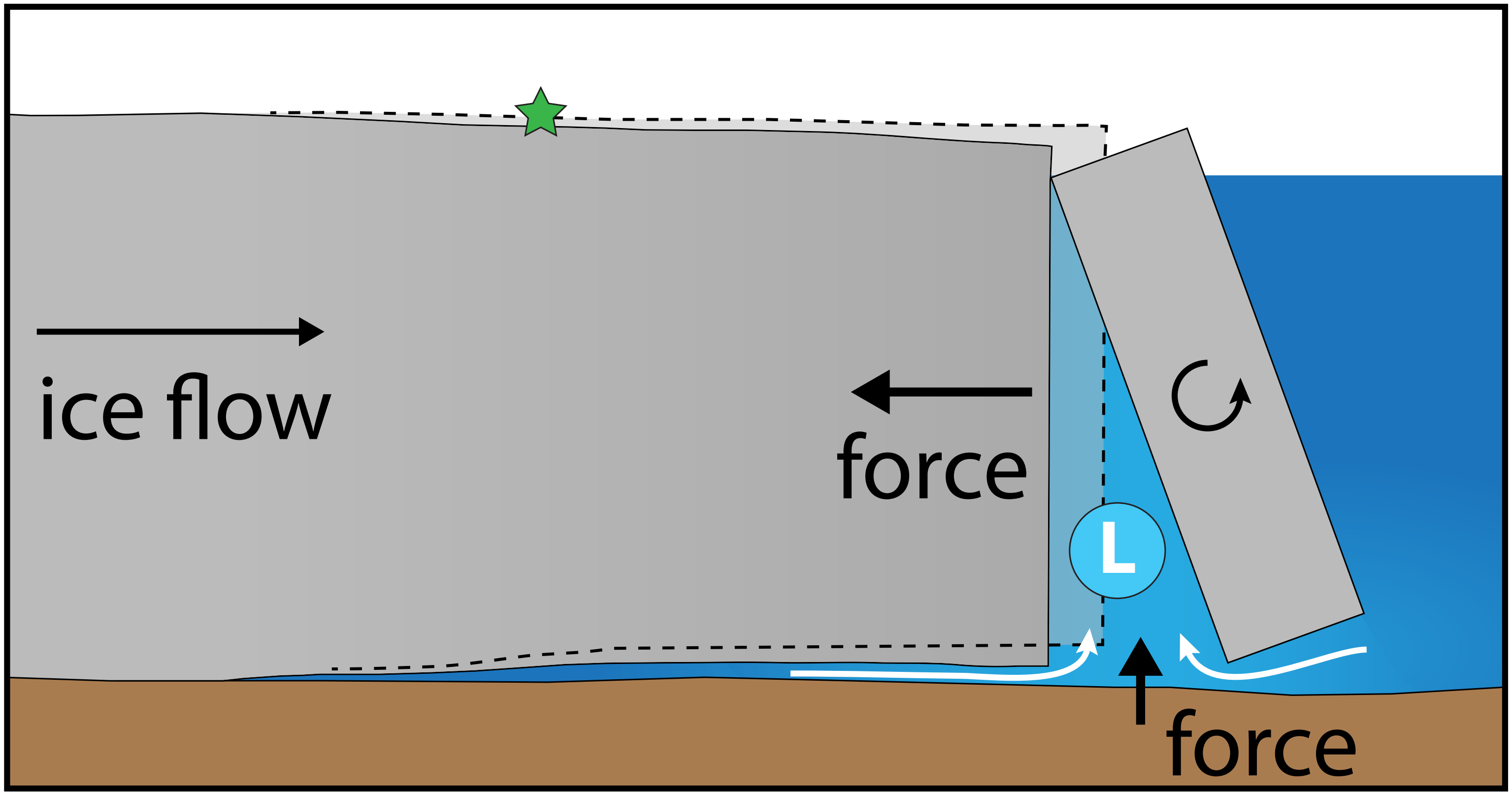
GPS along-flow

GPS vertical

(Murray et al., 2015)

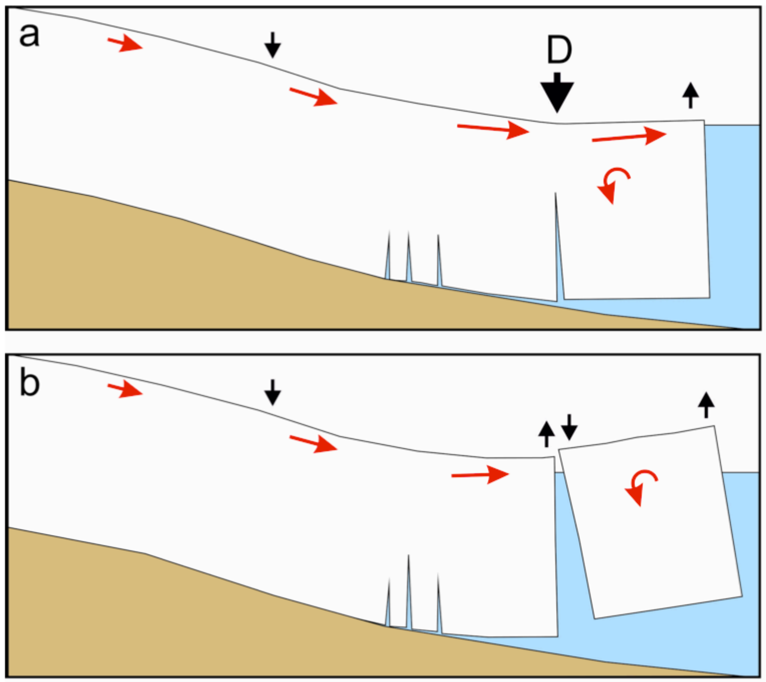
Earthquake source:

- horizontal force - reaction force due to iceberg acceleration away from glacier;
- vertical force - upward force due to dynamic pressure drop behind capsizing iceberg



(Murray et al., 2015)

Calving of (nearly) grounded ice: buoyancy-driven calving

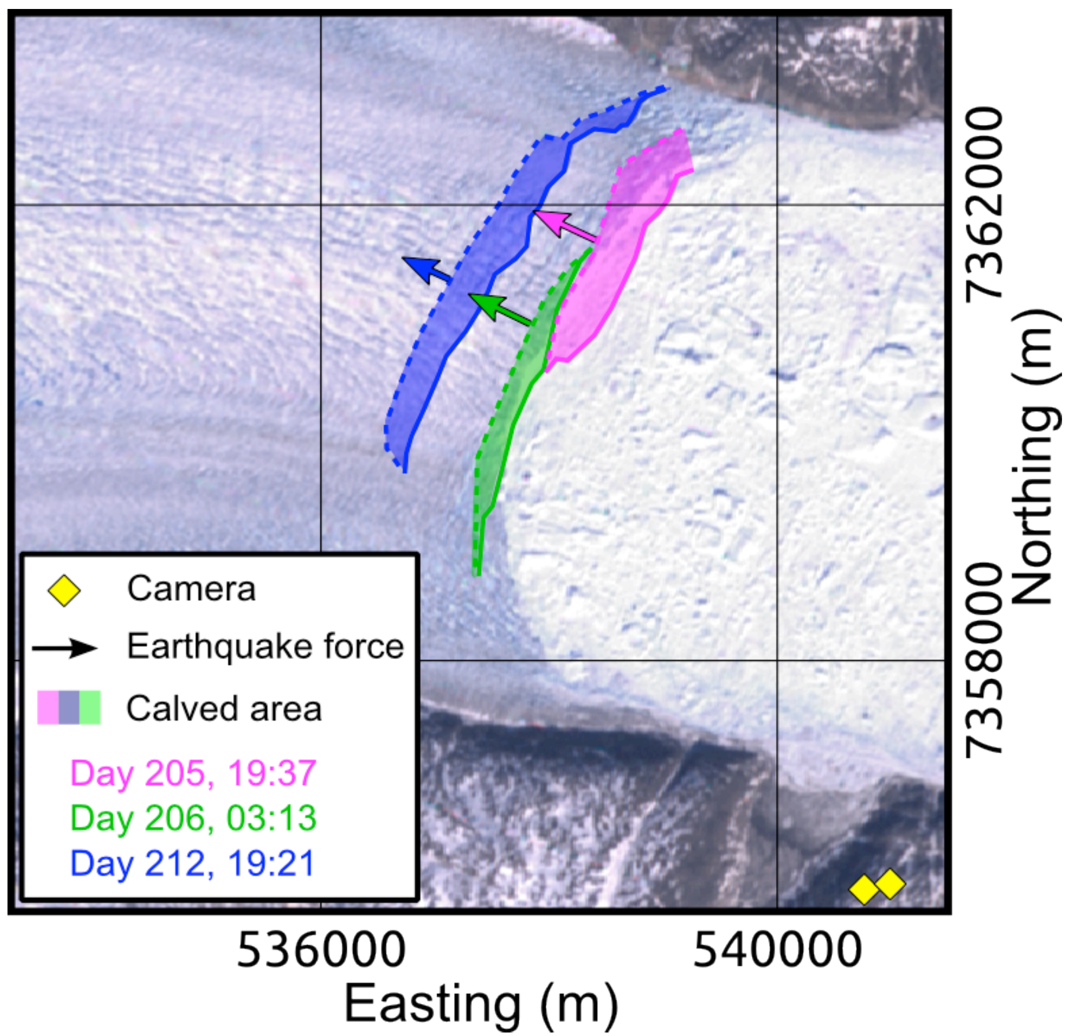


(Murray et al., 2014)

How many calving events are detected as glacial earthquakes?

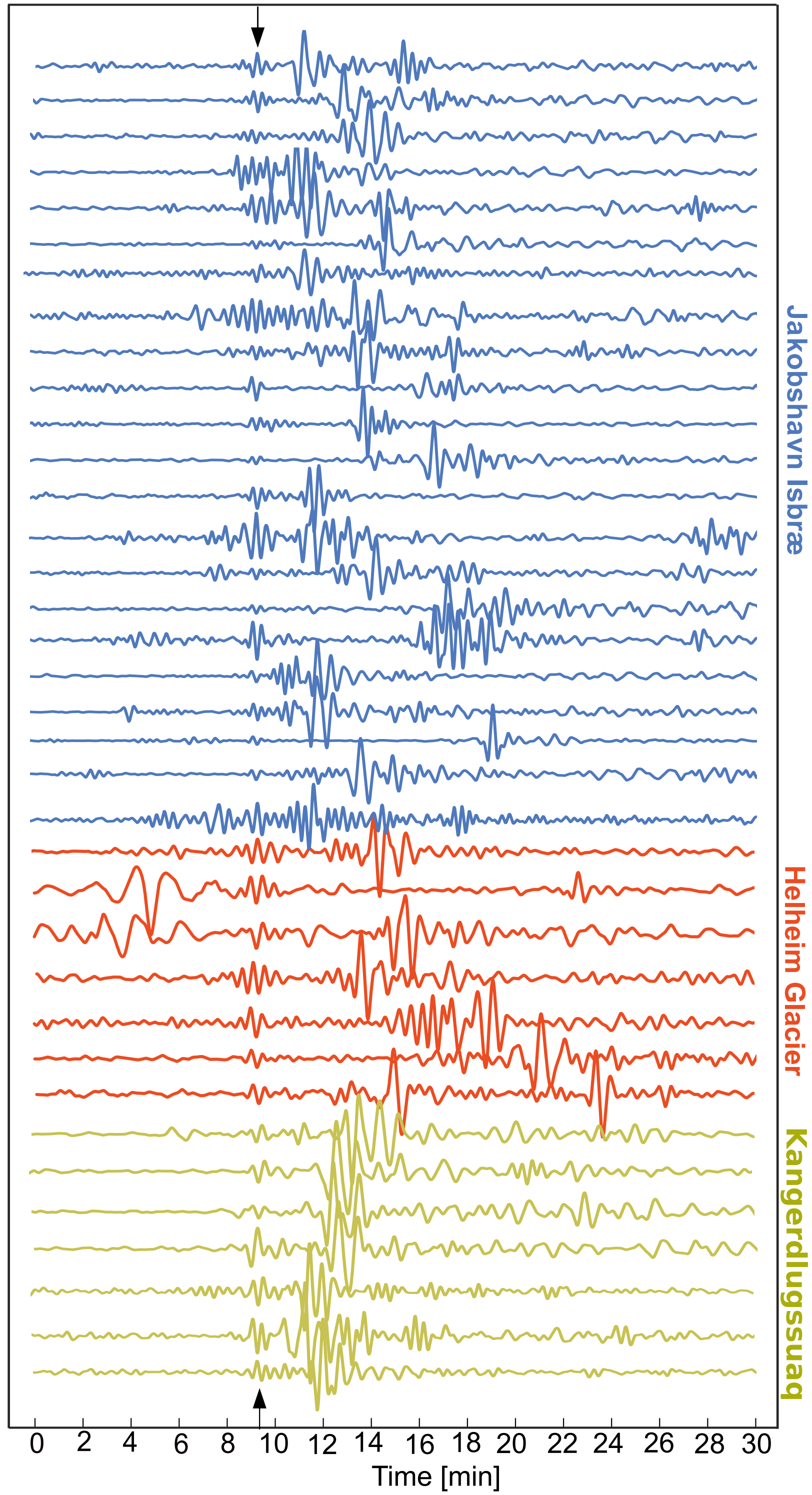
How many glacial earthquakes correspond to calving events?

Excellent agreement in geometry, and one-to-one correspondence between visually identified calving events and earthquakes

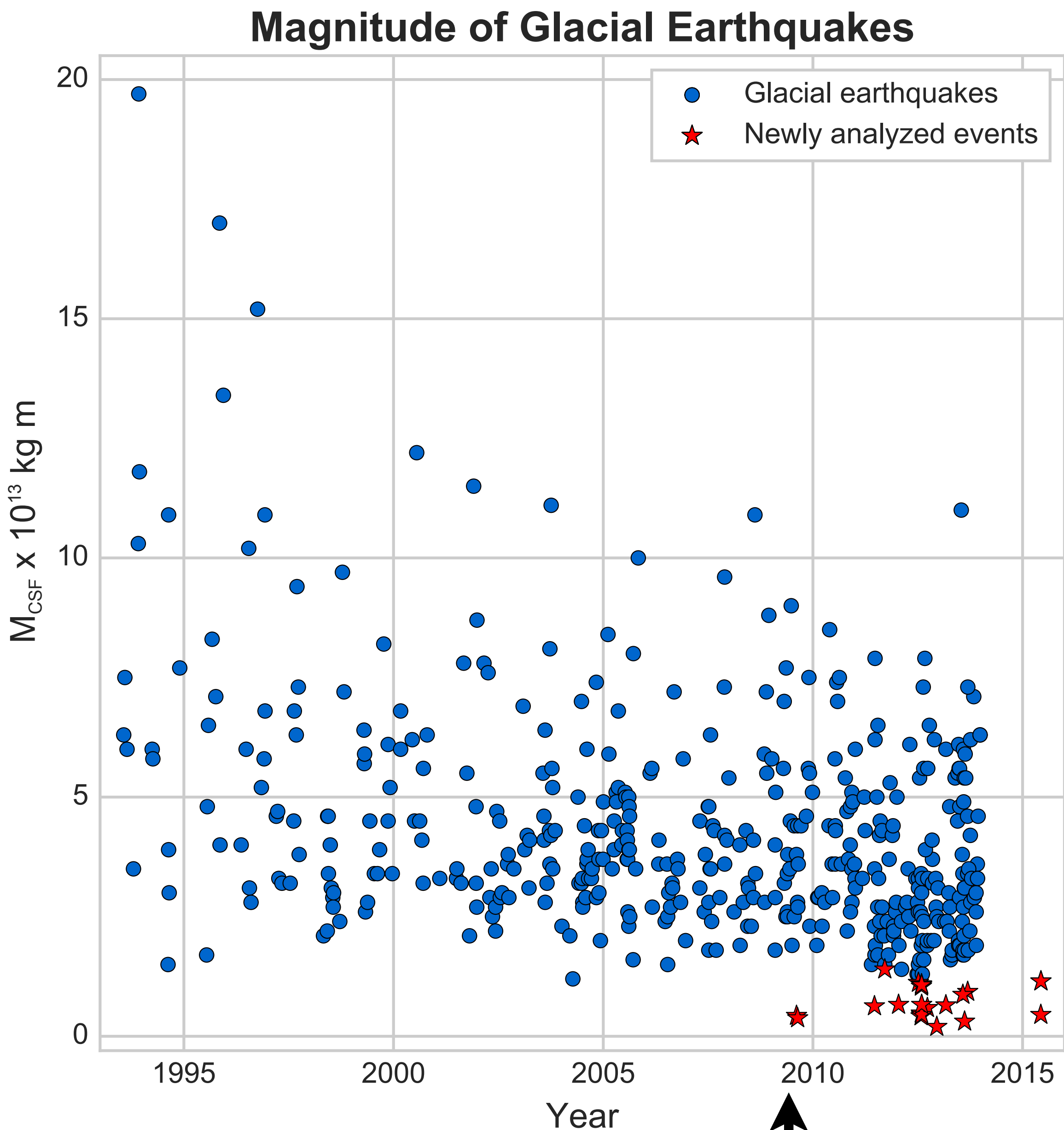


thanks to T.D. James, N. Selmes, T. Murray

Glacial-earthquake "precursors", from Kira Olsen



(ms in prep)



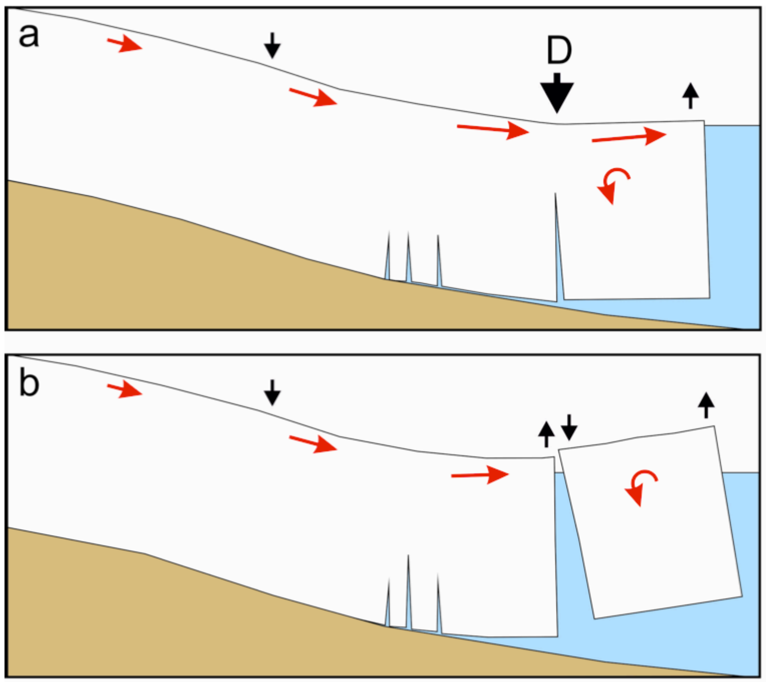
glacial-earthquake precursors: smaller calving events

July, 2009
First GLISN station installed

(K. Olsen)

(ms in prep)

Buoyancy-driven calving likely accounts for almost all dynamic mass loss during the calving (~summer) season at nearly grounded glaciers



(Murray et al., 2014)

Summary

- Solid Earth, hydrology, and ice dynamics are linked
- Seismology has a contribution to make at these boundaries
- Requires: high-quality data; high-quality data archiving and curation; interdisciplinary data and collaborations