Glacial Seismology

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These slides are only for educational purpose and all the content in them are taken from some research papers.
This literature review was done as a part of internship and I had tried to provide credits whereverrequired.

Iceberg Calving

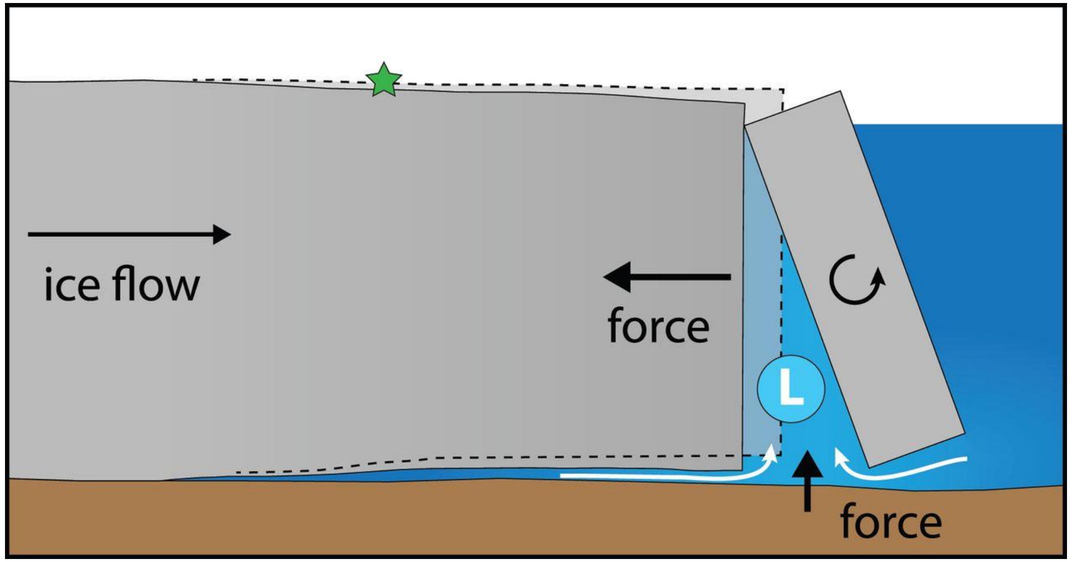
- Ice calving is the sudden release and breaking away of a mass of ice from a glacier edge.
- Capsizing of icebergs seems to be a necessary condition for a calving event to generate glacial earthquakes.

Iceberg calving is difficult to monitor as-

•Direct observations are expensive and often provide only estimates on calving volume.

•Satellite images are subject to temporal and spatial resolution constraints.

•Seismology can potentially monitor the activity of calving fronts remotely and with good temporal resolution. But, seismic signals to are affected by free fall height of iceberg and state of ocean surface.

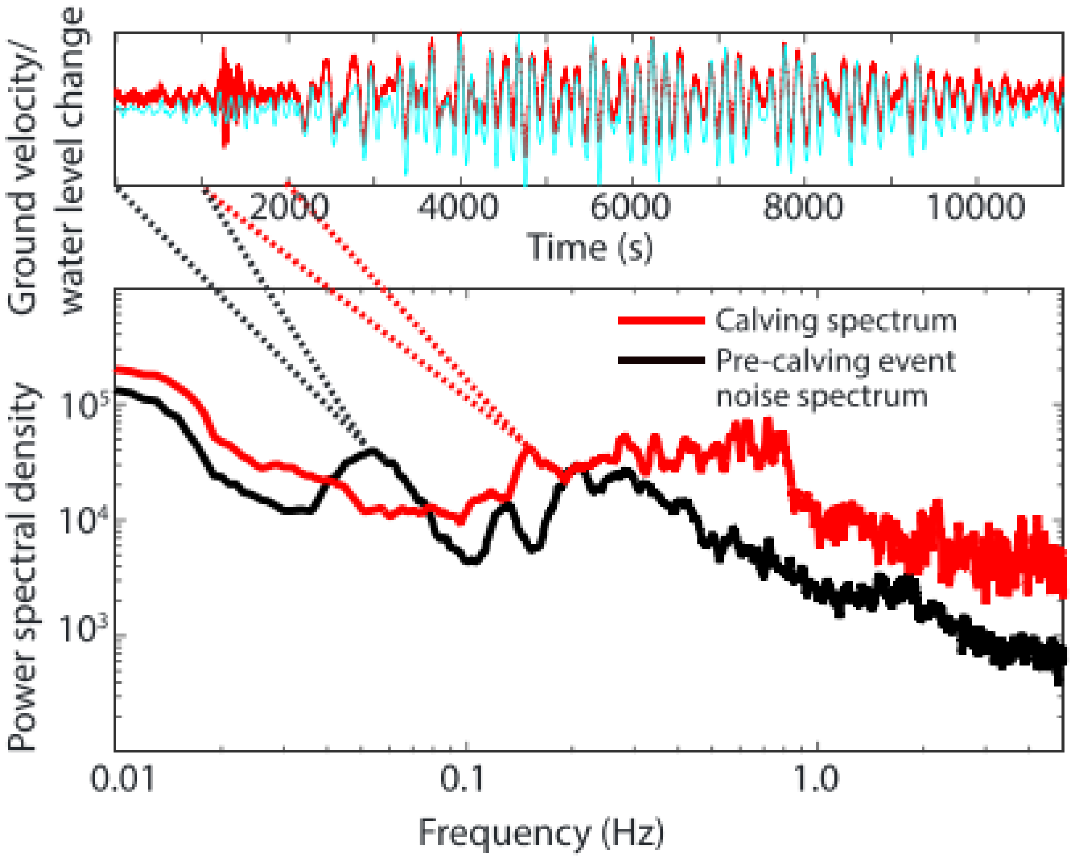


Cartoon of glacier terminus during calving event. Glacier deflection caused by a capsizing iceberg is shown relative to the initial glacier position (dotted line). Acceleration of the iceberg to the right exerts a force in the upglacier direction (left), leading to reverse motion of the GPS sensors (green star). Reduced pressure behind the iceberg (L) draws water from beneath the glacier and from the proglacial water, pulling the floating portion of the glacier downward and exerting an upward force on the solid Earth.

T. Murray 2015

Seismic signature of iceberg calving

Example1
Kangerdlugssup Sermerssua (Greenland)
23 august 2010



Example of a large-scale calving event (recorded at ~70 km distance) at Kangerdlugssup Sermerssua, a tidewater glacier in west Greenland region.

- Long Period of calving generated seismicity could be seen.
- Hour-long monochromatic oscillation prominently with periods of several minutes.
- Actual iceberg detachment lasts on the order of minutes, only, and occupies the spectrum at frequencies between 0.01 and 5 Hz.
- All other signals are generated by detaching icebergs impacting the ocean surface, fracturing and avalanching of debris, shifting of the fjord's debris cover and interaction between the detaching iceberg and the glacier terminus and/or fjord bottom.

Seismic signature of a calving event at Kangerdlugssup Sermerssua (Greenland), recorded on the broadband station NUUG of the Greenland Ice Sheet Monitoring Network (GLISN).

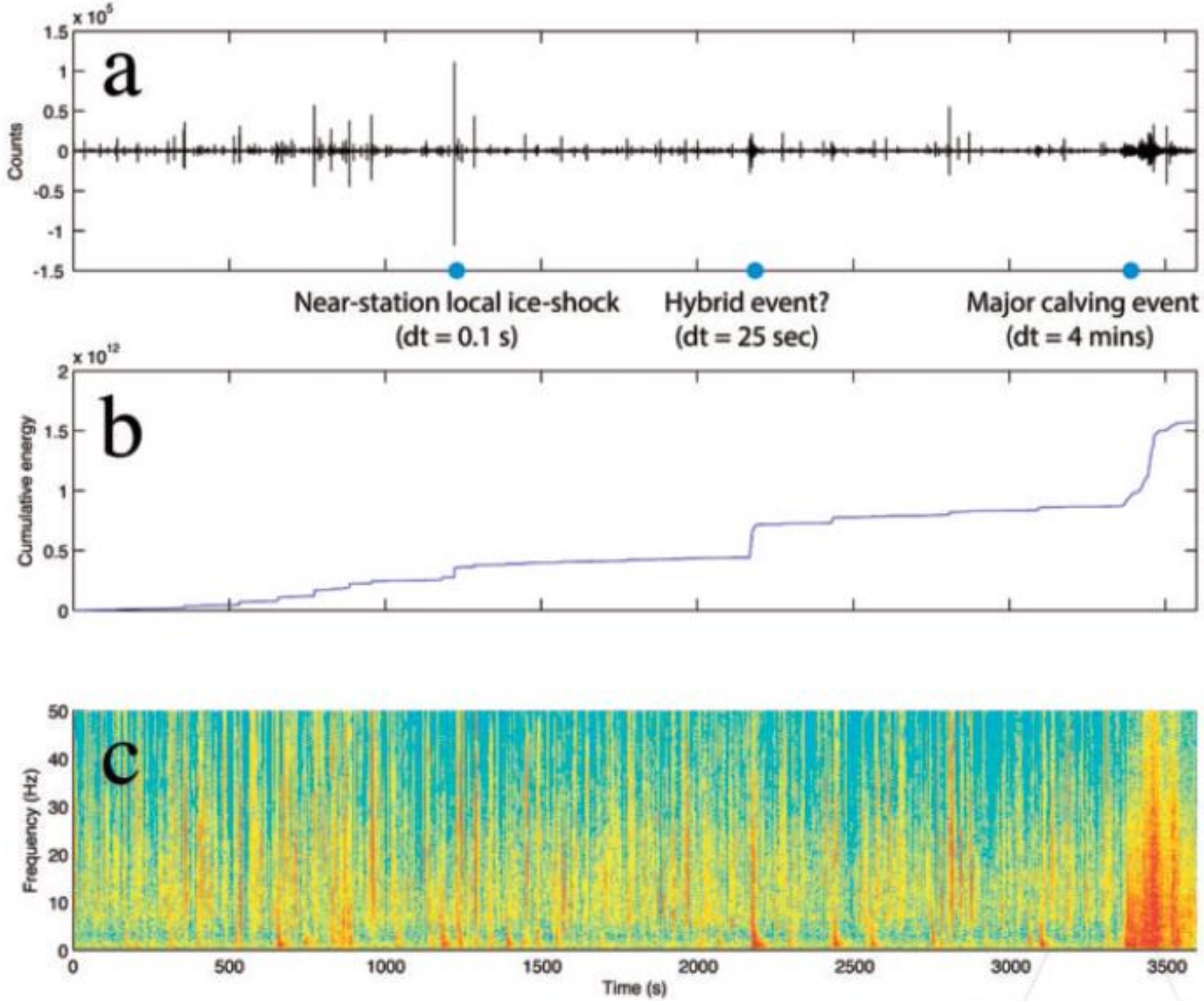
Podolskiy et al. 2016

Example2
Bowdoin Glacier, Greenland
18 July 2015

- <u>Multiple seismic events</u> were recorded that were associated with various processes, like surface crevassing, iceberg calving, iceberg rotations, tele-seismic earthquakes, harmonic tremors, lateral ice-cliff collapses onto rock, and presumably also hydro-fracturing.

- Hundreds of short, high-frequency (＞10 Hz) events and a few low characteristic frequency of ～ 1 Hz are seen.

- Finally, calving event is visible in the data as emergent, high-amplitude tremors with dominant frequencies between 0.2 and 5 Hz that last for a few minutes.



(a) Raw vertical-component seismic trace with markers indicating the three most common types of events: short impulsive ice-quakes, LP or hybrid events (the foot-like signals), and major calving events. (b) Cumulative energy . (c) Spectrogram

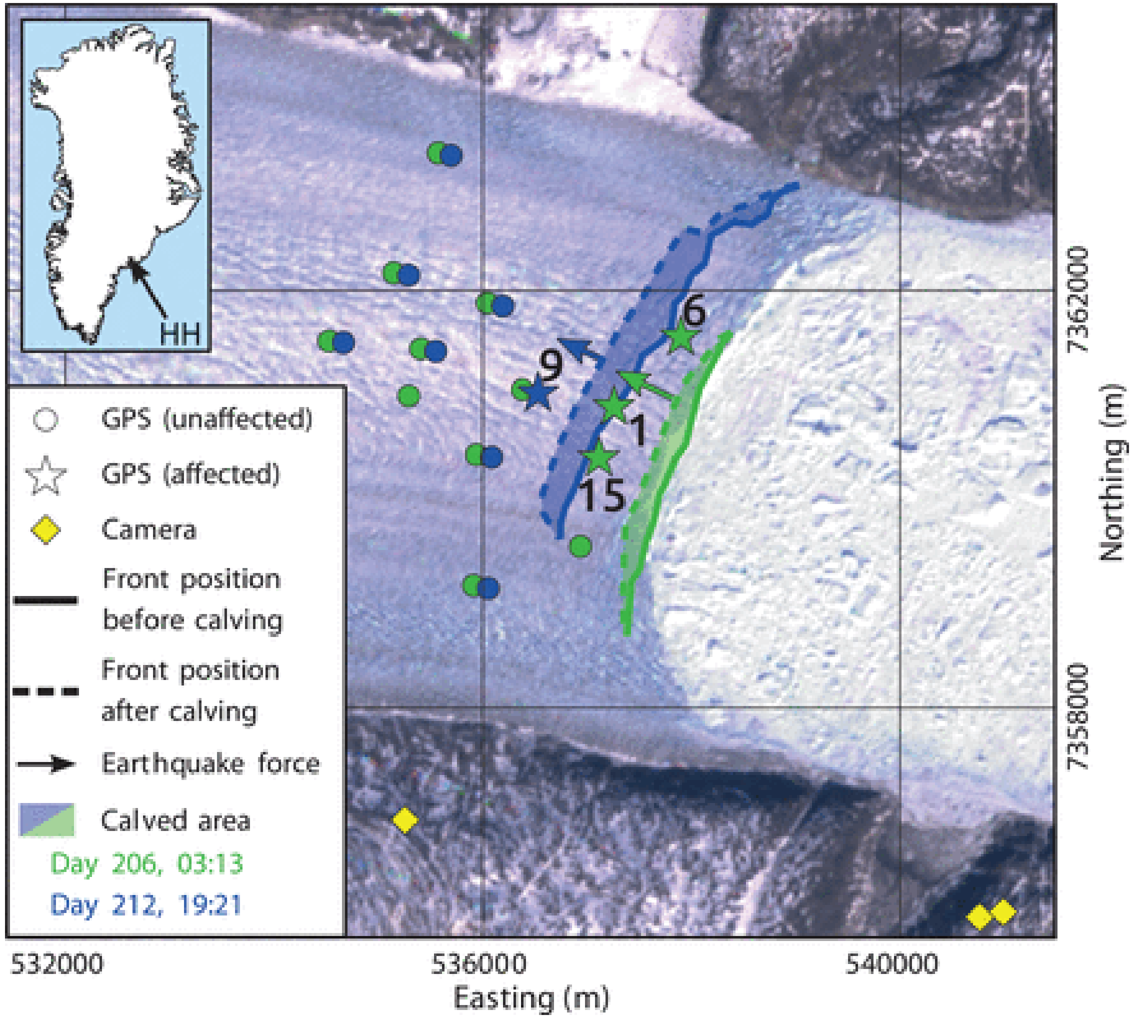
Podolskiy et al. 2017

What did you find common in both these examples?

1. Broad range of frequency.
2. Mixture of seismic signals from various events that lasts for hours before and after the main calving event.
3. The main calving event occurs only for several minutes duration.

Exceptions may occur during Antarctica's silent calving events, where capsizing does not happen. But the fracturing had been going on for years.

Case study : **Helheim Glacier, Greenland, 25 July 2013**



The location of GPS sensors and icebergs calved at Helheim Glacier (HH) for glacial earthquake.

•One-third to one-half of Greenland's total mass loss occurs through iceberg calving at the margins of tidewater-terminating glaciers.

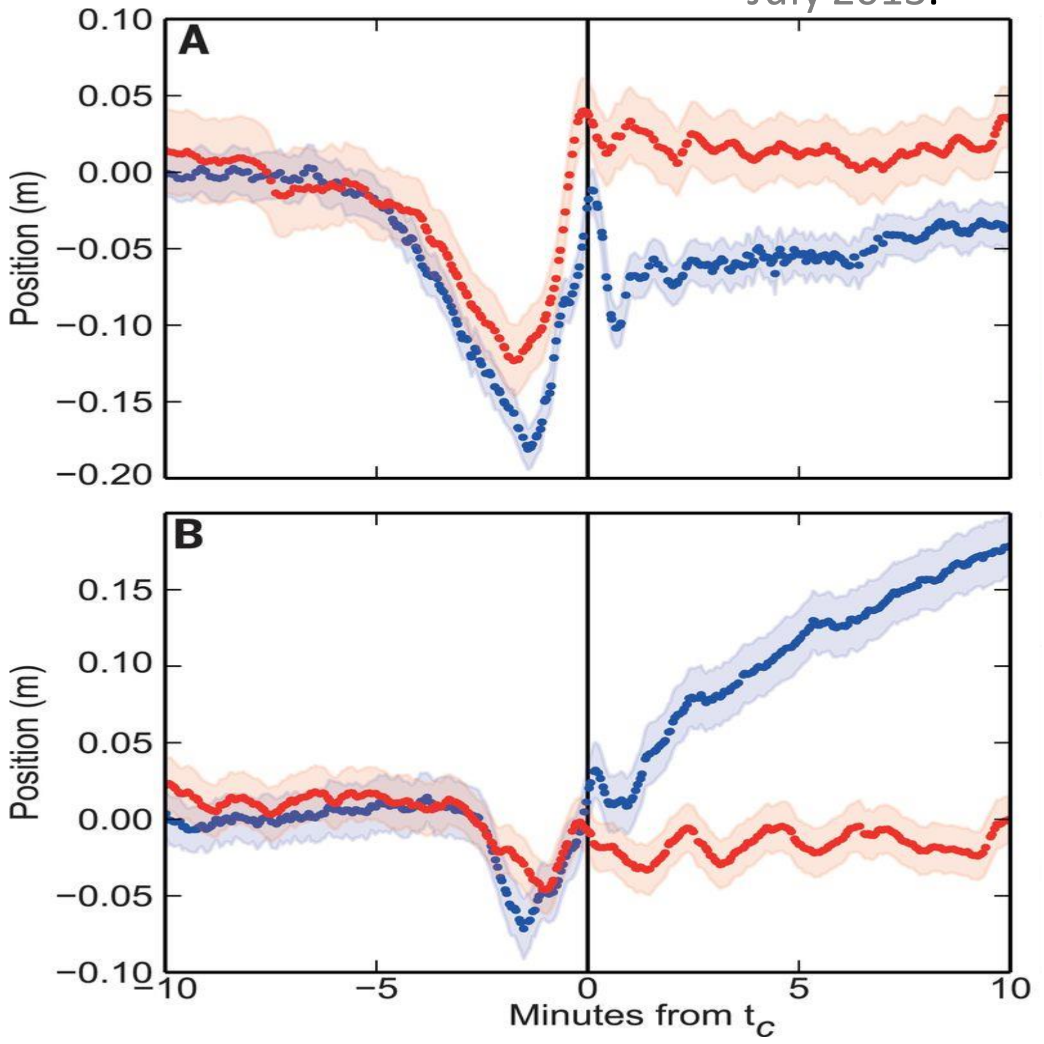
•Data was recorded at the calving margin of Helheim Glacier during 55 days in July–September 2013.

•GPS sensors captured glacier motion (with centimeter-level accuracy at a high temporal sampling rate) in positions very close to the calving front.

•Data from the global seismographic network were analyzed for the same time period to identify glacial earthquakes.

•Blue dots show along-flow displacement.
•Red dots show height.

(A) Sensor 1 on 25 July 2013.
(B) Sensor 9 on 31 July 2013.



Response of GPS sensors on glacier at the time of glacial earthquakes.

T. Murray et al. Science 2015;349:305-308

❖The earthquake centroid times (t_c) occurred near the end of the glacier's rapid rebound phase.

❖***The horizontal*** glacier deflection is consistent with a <u>model</u> - in which the reaction force on the glacier caused by seaward acceleration of the newly calved iceberg compresses the glacier front elastically.

❖***The downward*** deflection of the glacier front occurred in a region where vertical motion of the GPS sensors at tidal frequencies showed that the glacier is ungrounded and seawater is present beneath it.

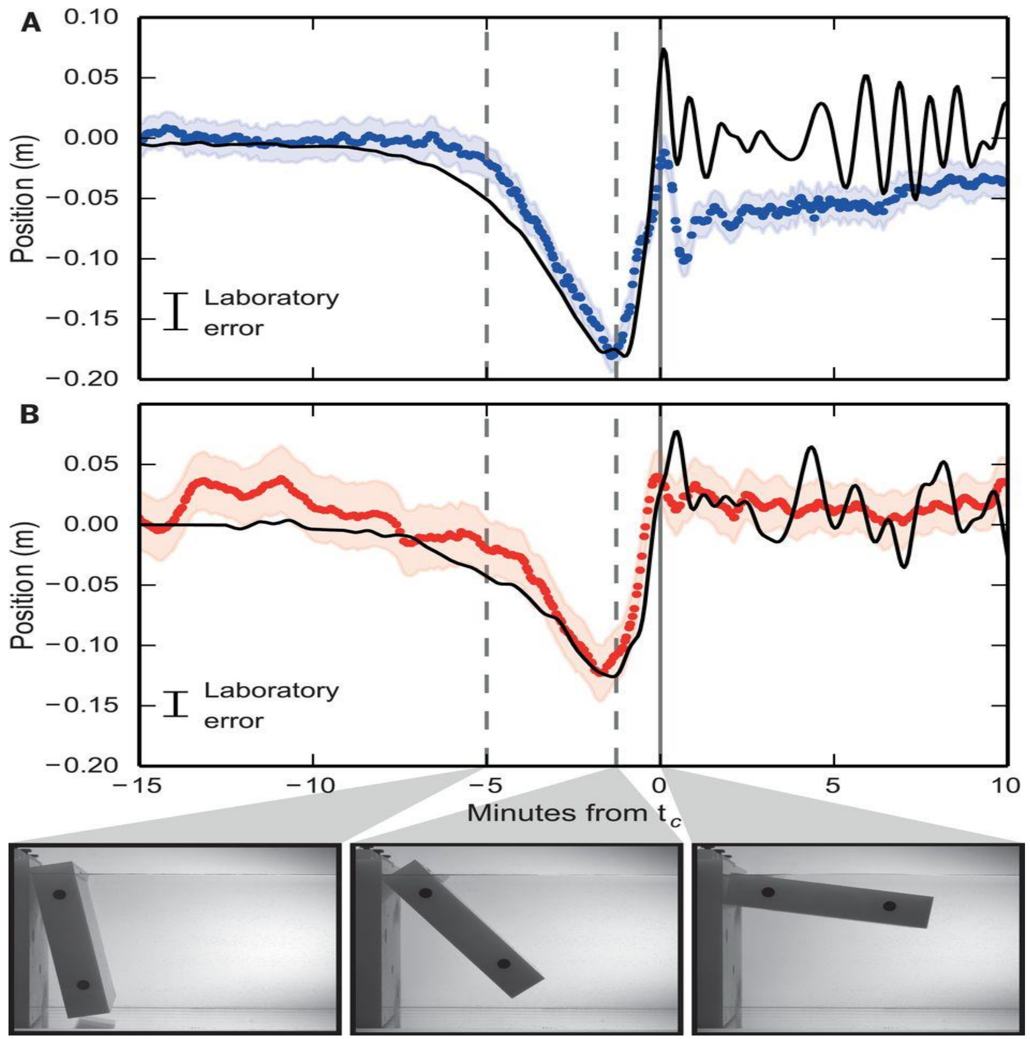
❖Iceberg rotation cause a low-pressure zone in the opening cavity between the iceberg and the glacier front. This pressure decrease lower the load on the bedrock, resulting in an upward force acting on the solid Earth, as observed in our seismic analysis. Therefore, pressure decrease near the calving front apply a net downward force on the glacier terminus, lowering the glacier surface.

Scaled laboratory data from glacier "terminus" during "iceberg" capsize event, compared with field observations.

(A) Horizontal displacement scaled from **force (black line**) compared with downflow GPS data (blue).

(B) Vertical displacement scaled from **pressure (black line)** compared with vertical GPS data (red).

(C) Photographs show stages of capsize at times marked by dashed lines and (solid gray line) t_c. The aspect ratio of the model iceberg is 0.22.



T. Murray et al. 2015

Glacier Hydraulics

Presence of water
-at ice bed interface affects the basal sliding and motion of ice sheet.
-at surface may cause enlarging of crevasses

Measurements of subglacial water flow and hydraulic conditions within and underneath the glacier are inherently difficult and expensive-

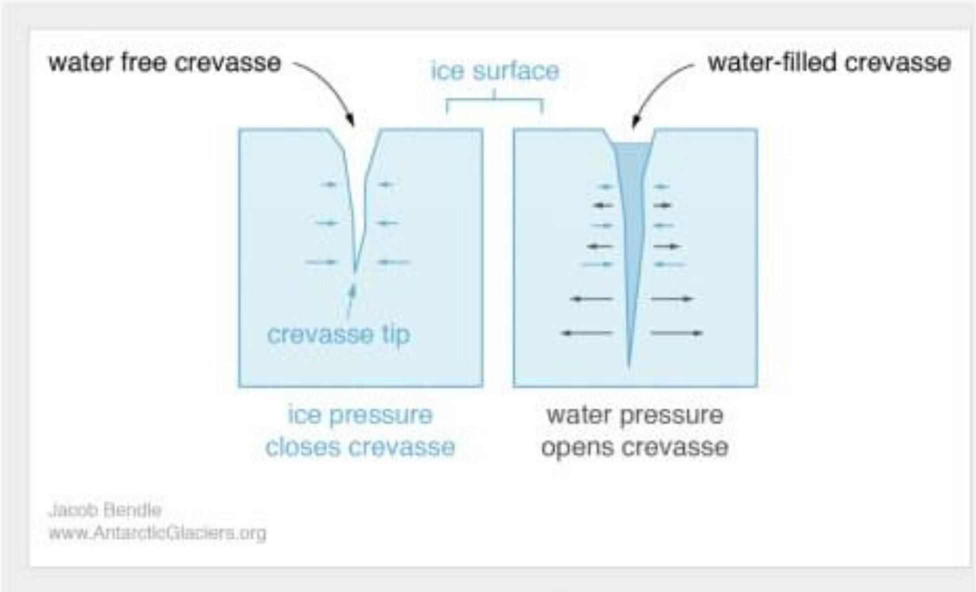
❖***Hot water drilling*** and subsequent ***borehole*** instrumentation with pressure sensors, cameras, inclinometers, and temperature gauges gives us important insights but only in the form of <u>point measurements</u>.

❖***Radio echo sounding and active source seismology*** can target a wide region and resolve drainage channel development within the ice or hydraulic changes within the bed. However, these measurements are difficult to repeat regularly over an extended time period and therefore provide distinct <u>snapshots in time only.</u>

❖***Passive seismic techniques*** can target a region of the glacier or ice sheet, which is <u>constrained by the spatial extent</u> of the monitoring network, noise level of background seismicity, and/or the strength of targeted seismic signals.

Hydrofracturing

❖Water present in crevasses causes it to expand by applying pressure on its walls.
❖Water level within the crevasse affects the depth to which surface crevasse penetrate, therefore presence of crevasse icequakes at intermediate depths provides us evidence for englacial water.
❖The gradual increase in icequake occurrence depth is related to increased water levels in cracks.
❖Seismic measurements on the dry polar Taylor Glacier, Antarctica, revealed that even small meltwater input promotes hydrologically triggered fractures.



Water Resonance

❖Sometimes monochromatic wave train is observed after a faulting icequake event.

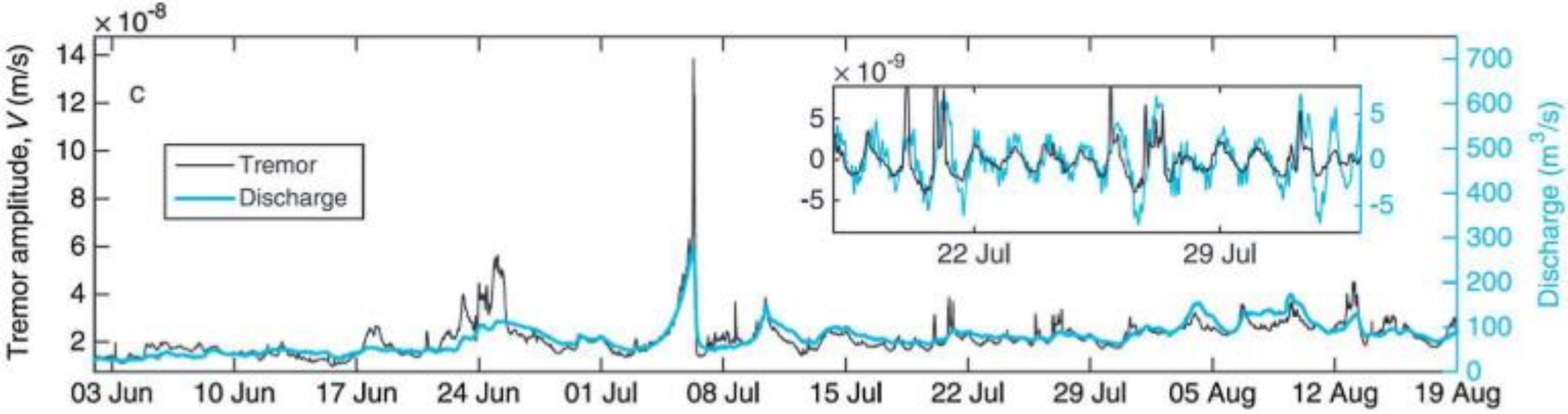
❖This occurs when some water channel is present nearby the fault.

❖So, fault causes oscillations in water inside the channel, which in turn keep oscillating and applying pressure on glacial walls, causing monochromatic waves for long time even after icequake event.

❖These resonance peaks could be used to understand the geometry of the water channels present beneath or inside the glacier.

Water flow- seismic tremor

❖Particles in flowing fluid and water turbulence in subglacial and englacial water flow emits seismic energy creating glaciohydraulic tremors. This connects us to the fluvial seismology.
❖Correlation between glaciohydraulic tremor amplitude and subglacial discharge has been recorded (in fig. below).
❖Seismic noise at a glacier is seen to be highest during the warmest part of the day, due to maximum melt runoff.



Glaciohydraulic **tremor amplitude, V. (black)** and water discharge (blue) into Mendenhall Lake, Alaska

Podolskiy et al. 2016

Glacial lake drainage- Glacial lake outburst flood

GLOFs have three main features:

❖They involve **sudden** (and sometimes cyclic) releases of water.

❖They tend to be **rapid events**, lasting hours to days.

❖They result in **large downstream river discharges** (which often increase by an order of magnitude).

J. Maurer 2020 Bhutan GLOF location satellite image

There are two main settings in which glacial lakes form:
(1) behind **moraine dams**, and (2) behind **ice dams**.

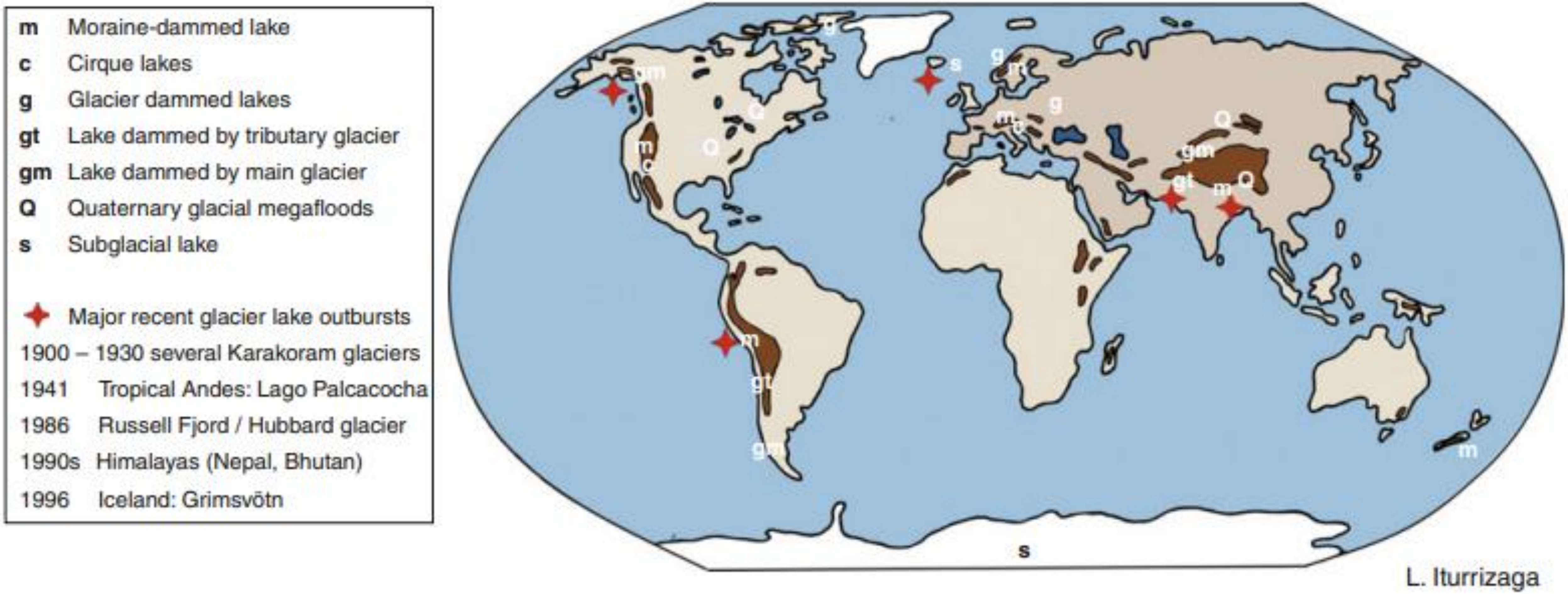
❖We need to make efficient strategies to predict outbursts and design reliable early warning systems to minimize destructive impacts by continuously monitor flood evolution through time.

❖While satellite observations can help identify regions of high GLOF risk and quantify geomorphic impacts after occurrence, they cannot capture GLOF events in real time.

❖Numerical flood models can be used to simulate dam outbursts and flood waves, yet require many physical parameters as input, which are often unknown or poorly con-strained.

❖These problems could be resolved by seismological study of the event.

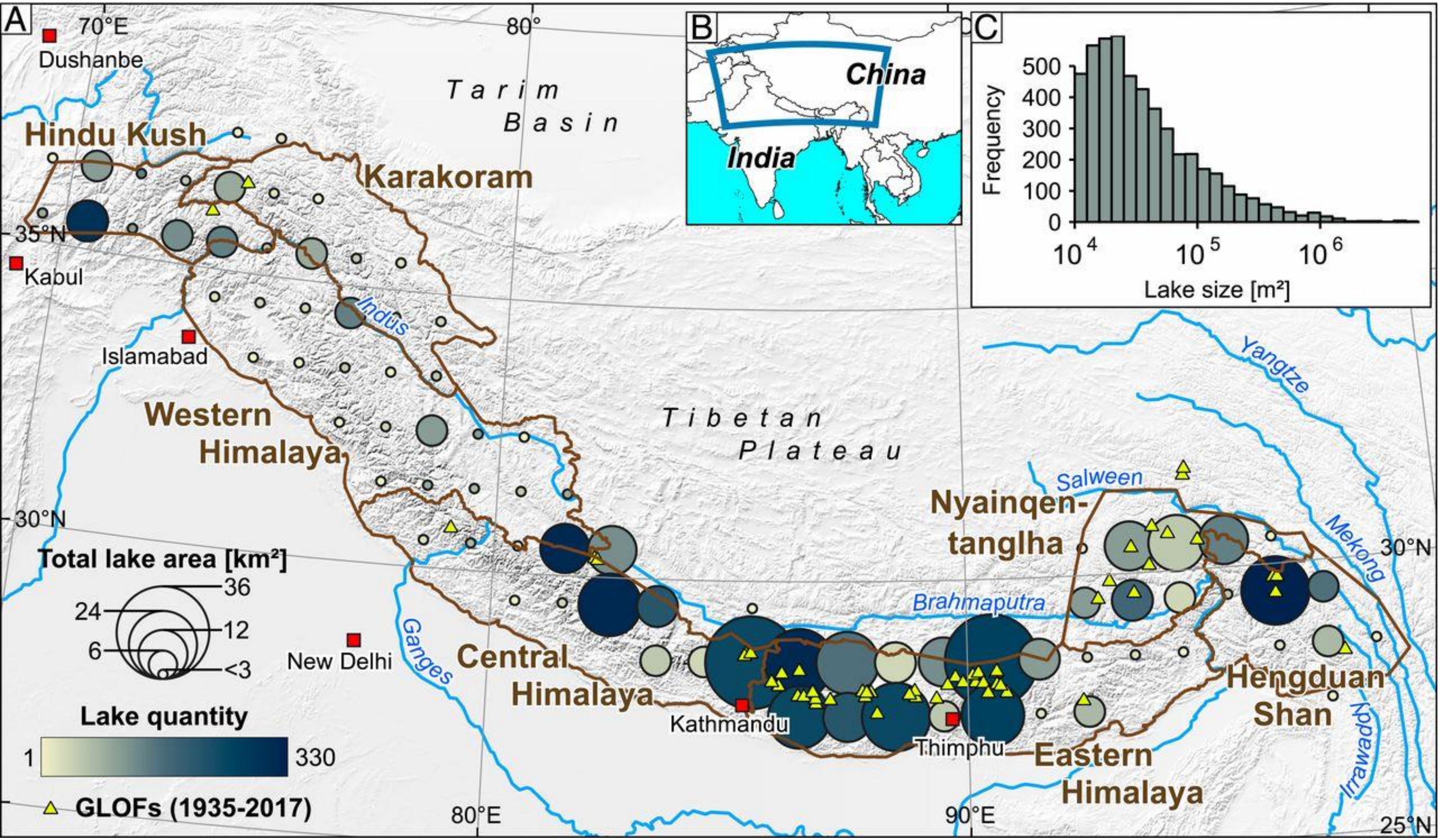
❖But still quantitative in situ observations of GLOFs are less because it is limited to rare situations where preinstalled instruments are co- incidentally located in the same valley as the GLOF.



Glacier Lake Outburst Floods, Figure 1 Recent worldwide distribution of glacier lakes and potential glacier lake outbursts areas as well as key localities of Quaternary megafloods. Internal glacier lakes (supraglacial, englacial, subglacial) may exist at all glaciers causing catastrophic floods.

L. Iturrizaga 2011

Case: Poo Chhu Valley Bhutan 1994

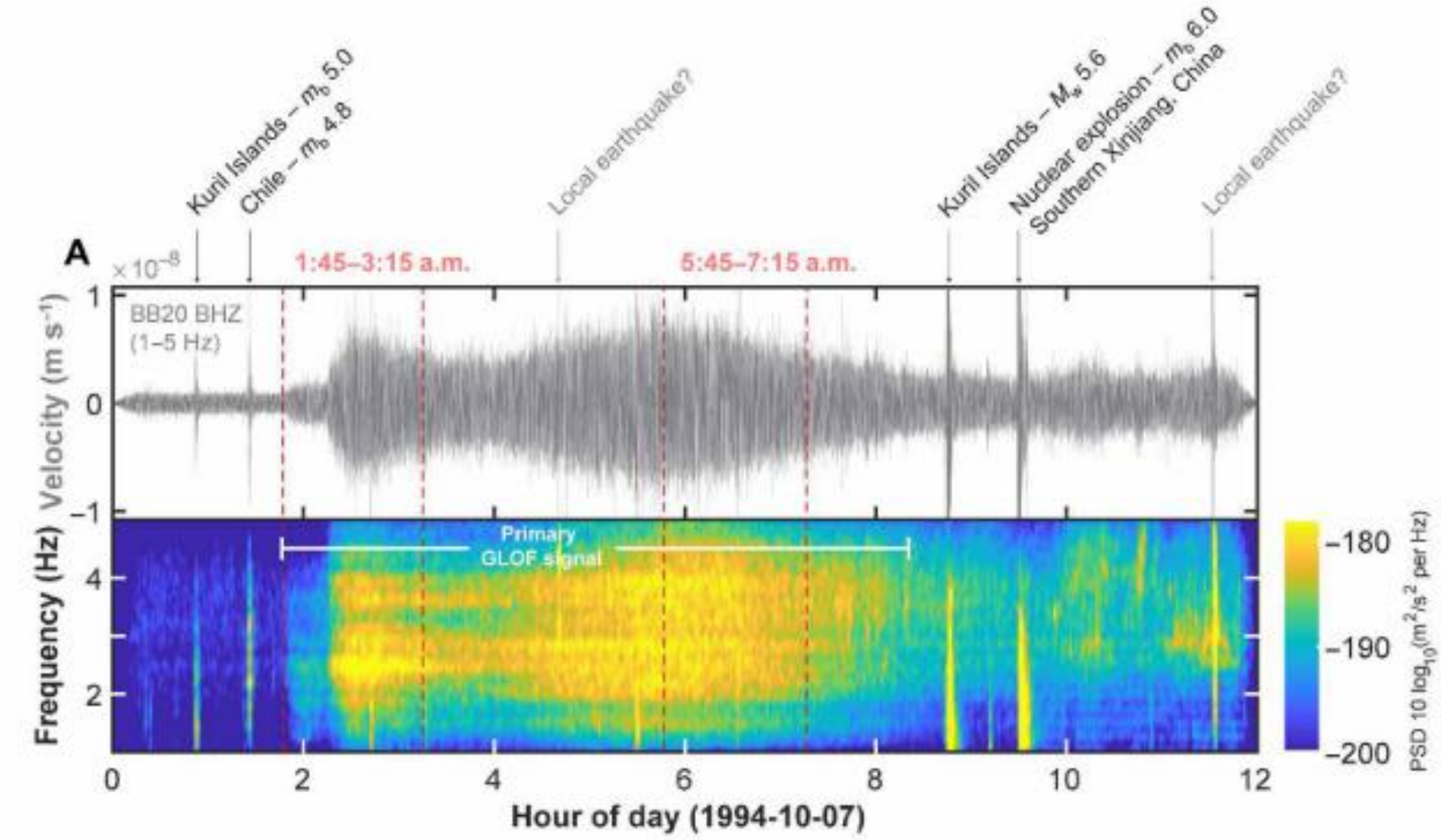


Georg Veh et al. 2019

Moraine-dammed lakes in the Himalayas. Bubbles are scaled to the total lake area, and color-coded to abundance.

Reported GLOFs (yellow triangles) have occurred most frequently in the past eight decades in Himalayan regions where glacier lakes are largest.

Data was recorded by five seismometers (with locations ranging from approximately 75- to 130-km distance from the breach point) as a clear high-frequency (1 to 4 Hz) signal lasting several hours.



Signal power began increasing at 2 a.m. And reached a maximum at 6:00 a.m. [with frequency content ranging from approximately 1 to 5 Hz.]

During this interval, the flood wave passed through the main branch of the Pho Chhu and impacted Punakha at approximately 7:00 a.m. based on eyewitness accounts.

Antarctica vs Greenland vs Himalaya

- The Greenland earthquakes are associated with glacier calving that involves large displacements of relatively small (~1 km3) volumes of ice.
- In Antarctica, slow-sliding events involving large volumes (thousands of cubic kilometers) of ice and small displacements.
- In Himalayas, earthquakes are associated with GLOFs and major ice mass loss occurs in form of water, either by flood or by melting.

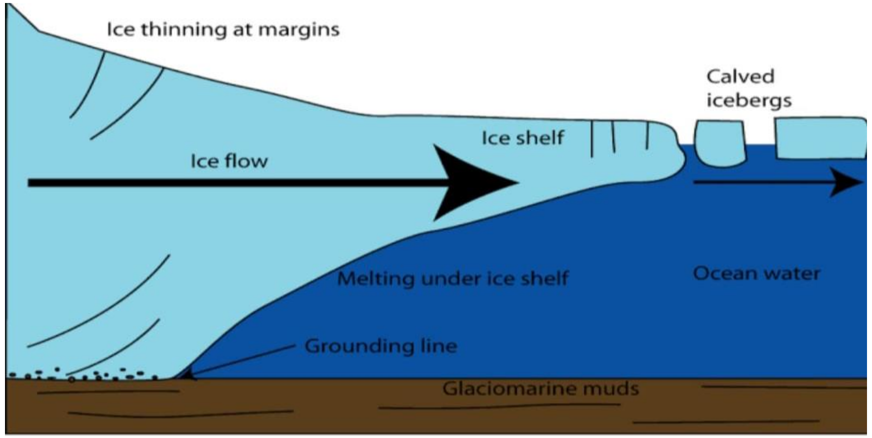


Diagram: Glacial tongue

	Antarctica	Greenland	Himalayas
Major way of losing ice mass	Slow sliding Calving	Calving	Hydrofracturing GLOFs
Calving 1. position	Occurs far from the grounding line	Occurs near the grounding line	Occurs over bedrock only
2. process	Ice breaks slowly over time without much noise	Capsizing is must; Faster than Antarctica	Dry calving; due to hydrofracturing of hanging glaciers
3.seimisity	Very less seismicity, silent type	High seismicity for hours or days	X
Glacial floating tongue	Many kms long	Few kms long	No tongues because no nearby sea
Slow sliding event Basal stick slip	Occurs majorly in antarctica	Present but not much detected by seismometers	X
Crevasses	Present;	Present; major cause of calving initiation	Present; creates major seismicity during night
GLOFs	Seen only on Antarctic peninsula or on hills	Few GLOFs have been reported till now	Majorly occurring due to slope.
Tectonic seismicity	Very quiet	Little or no activity	Major earthquake zone